Results and highlights from *Planck*

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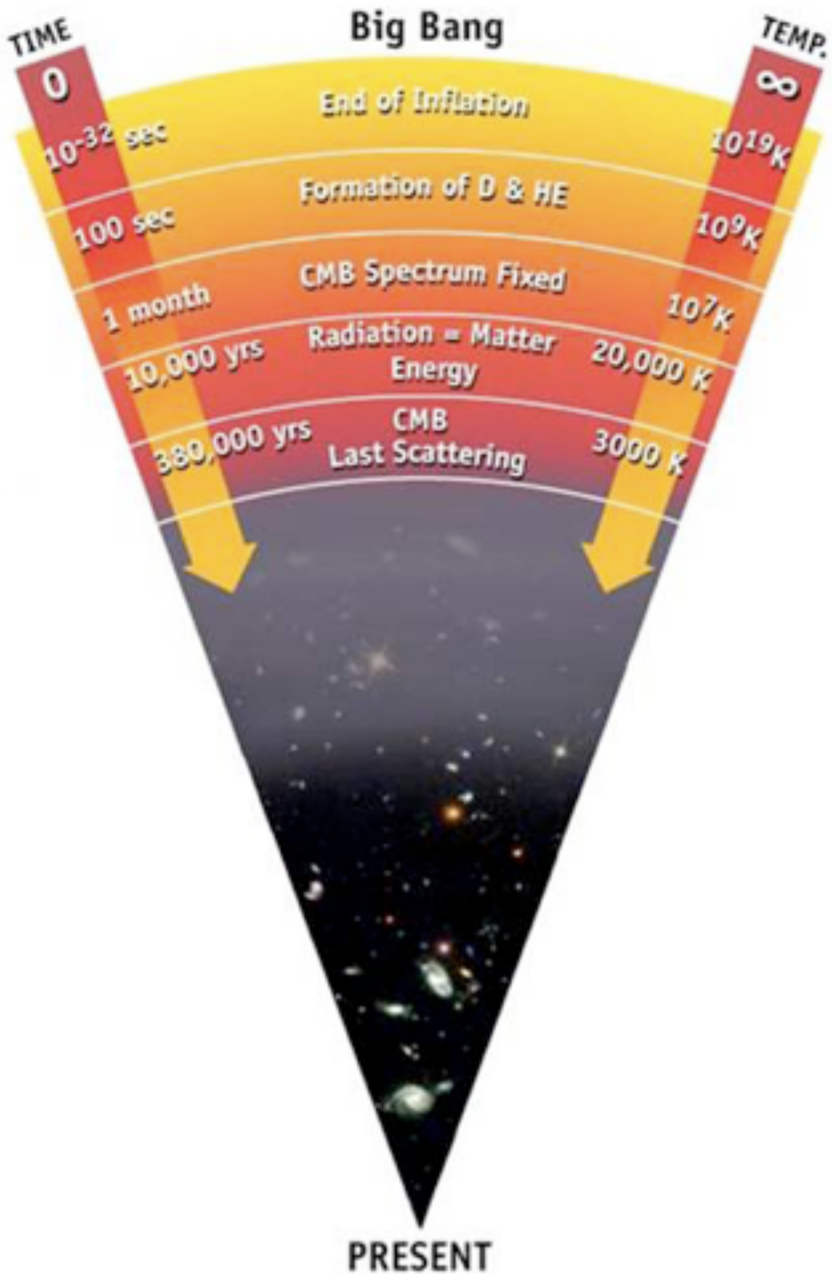
Standard cosmological model



Thermal history: early universe is hot dense plasma with small perturbations propagating as sound waves

At z ~ 1100, temperature is 3000 Kelvin. Free protons and electrons combine to form neutral hydrogen ("recombination"); universe becomes transparent.

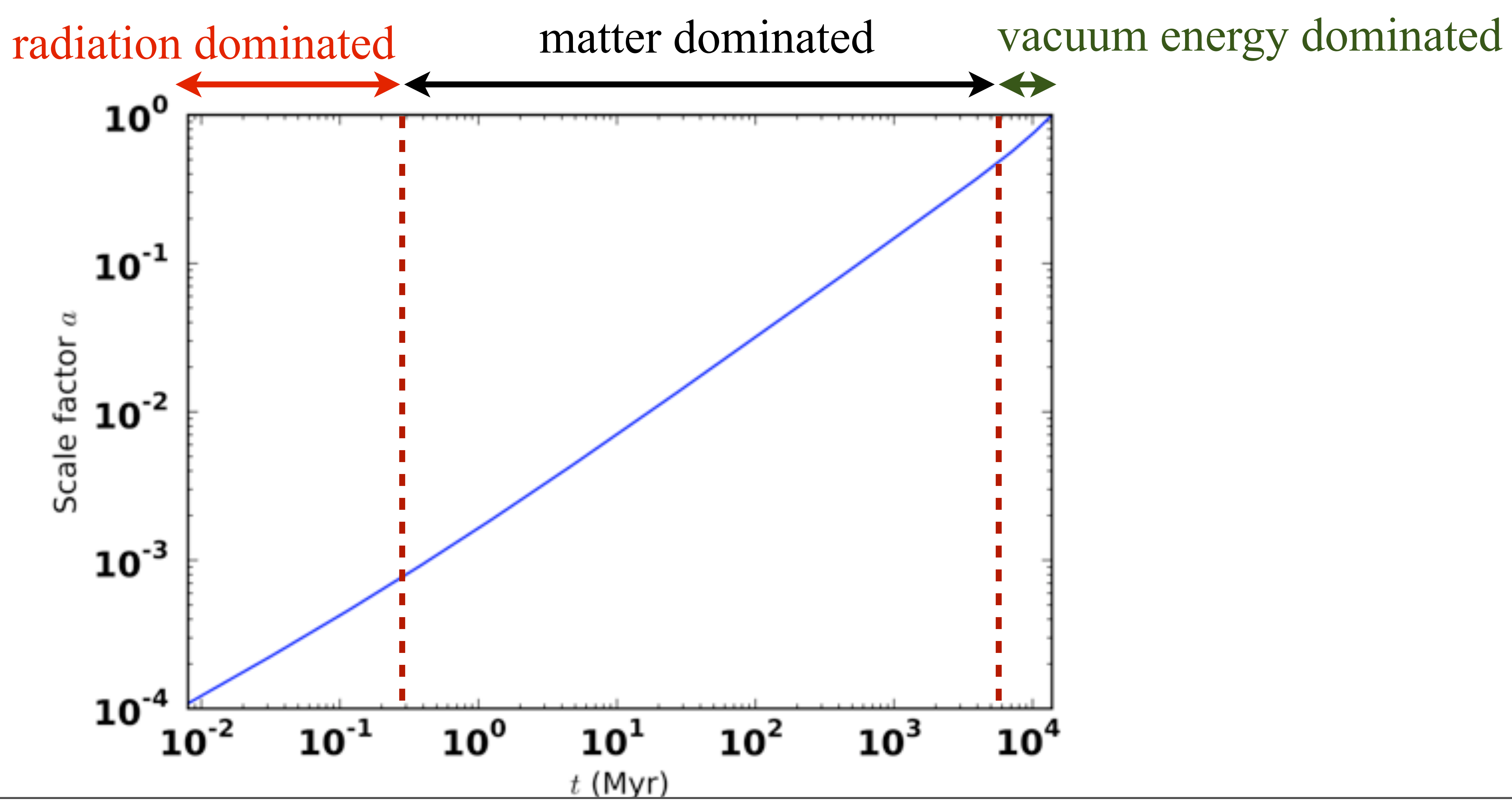
Small perturbations grow via gravitational instability; get order-1 perturbations at z~0. Photons which have been freestreaming since z=1100 are observed as the CMB.

Expansion history: scale factor a(t) evolves via Friedmann equation

$$H(a) = \frac{d\log a}{dt} = \left(\frac{8\pi G}{3}\rho_{\rm tot}\right)^{1/2}$$

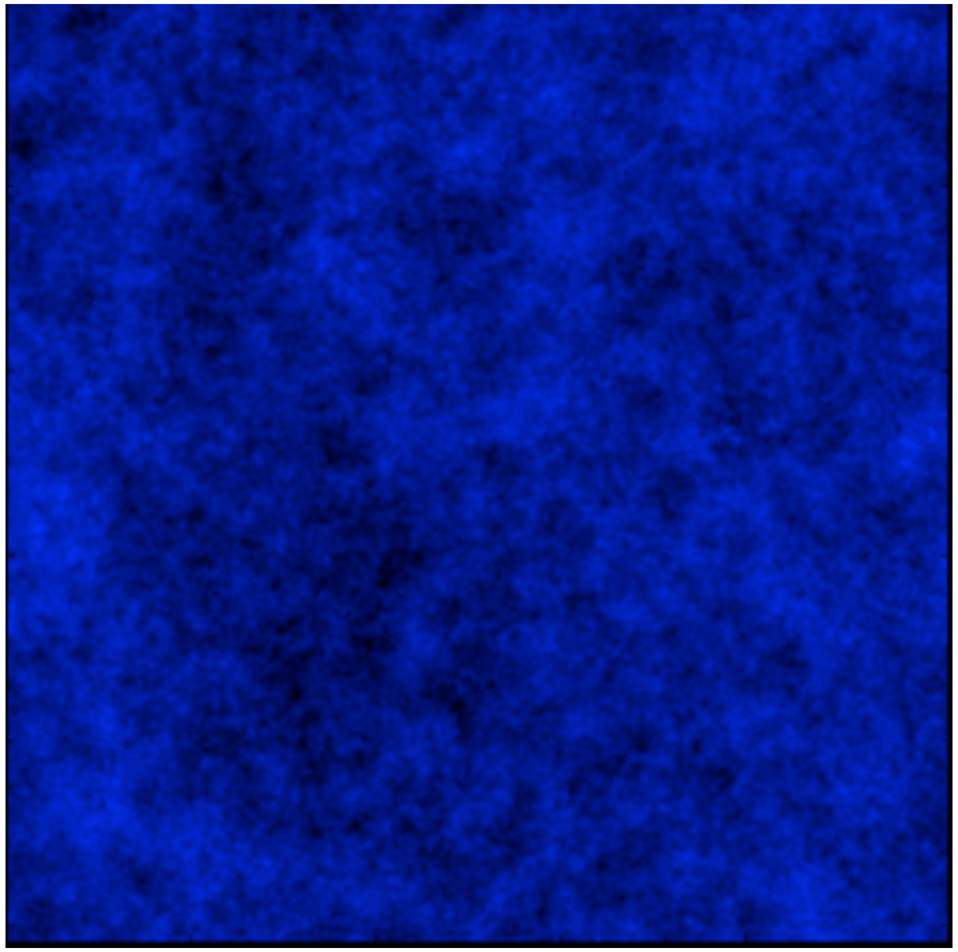
Cosmologists' parametrization:
(3 parameters since
$\Omega_b + \Omega_c + \Omega_\Lambda = 1$)

$$\begin{cases} H_0 = \text{Hubble parameter at } z = 0 \\ \Omega_\Lambda = \rho_\Lambda/\rho_{\rm tot} \ \text{ at } \ z=0 \\ \Omega_c = \rho_c/\rho_{\rm tot} \ \text{ at } \ z=0 \\ \Omega_b = \rho_b/\rho_{\rm tot} \ \text{ at } \ z=0 \end{cases}$$



Perturbations: initial perturbations are "adiabatic"

$\zeta =$ time delay between constant density and spatially flat slicings



ζ is a nearly scale-invariant Gaussian field

Each Fourier mode $\zeta(\mathbf{k})$ is an independent Gaussian random variable with variance

$$\langle \zeta(\mathbf{k}) \zeta(\mathbf{k}')^* \rangle = A_\zeta k^{n_s - 4} (2\pi)^3 \delta^3(\mathbf{k} - \mathbf{k}')$$

(Scale-invariant corresponds to $n_s = 1$)

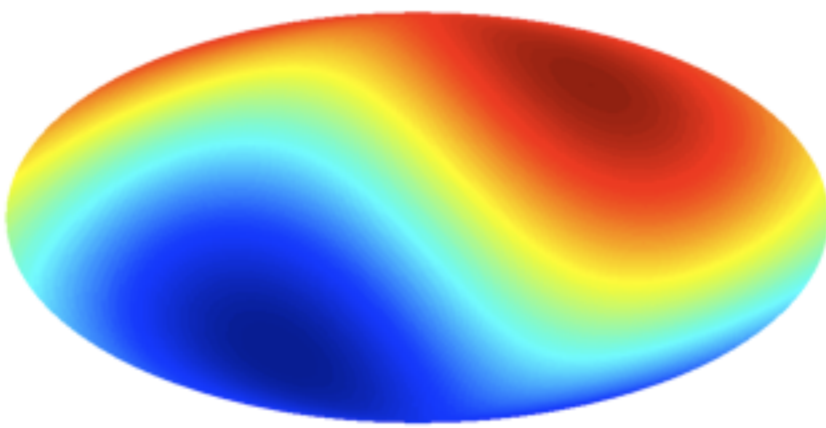
In this talk, "standard cosmological model" means 6 parameters:

$$\{H_0, \Omega_c, \Omega_b, A_\zeta, n_s, z_{\text{rei}}\}$$

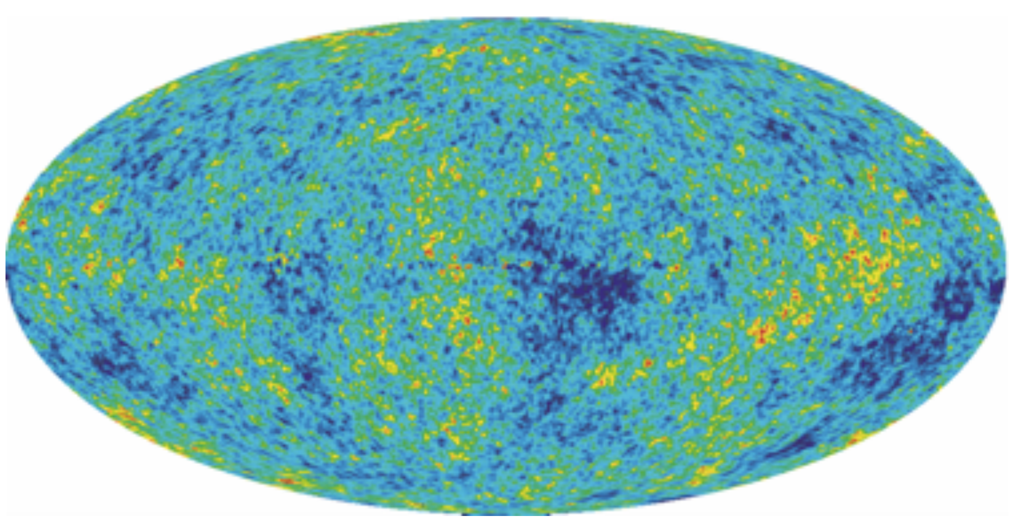
nuisance parameter: redshift of reionization

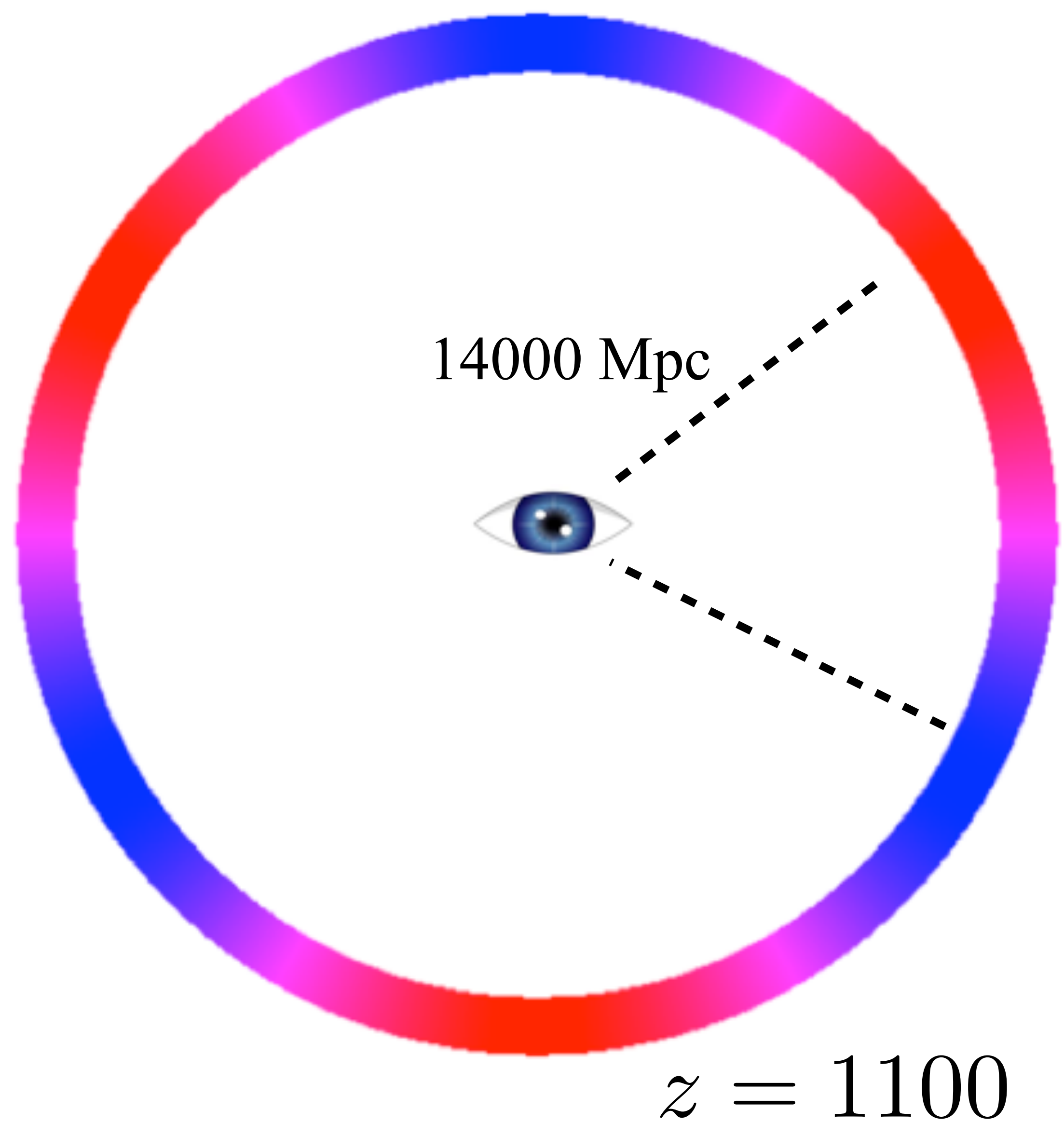
CMB sky

monopole: blackbody, 2.7255 K



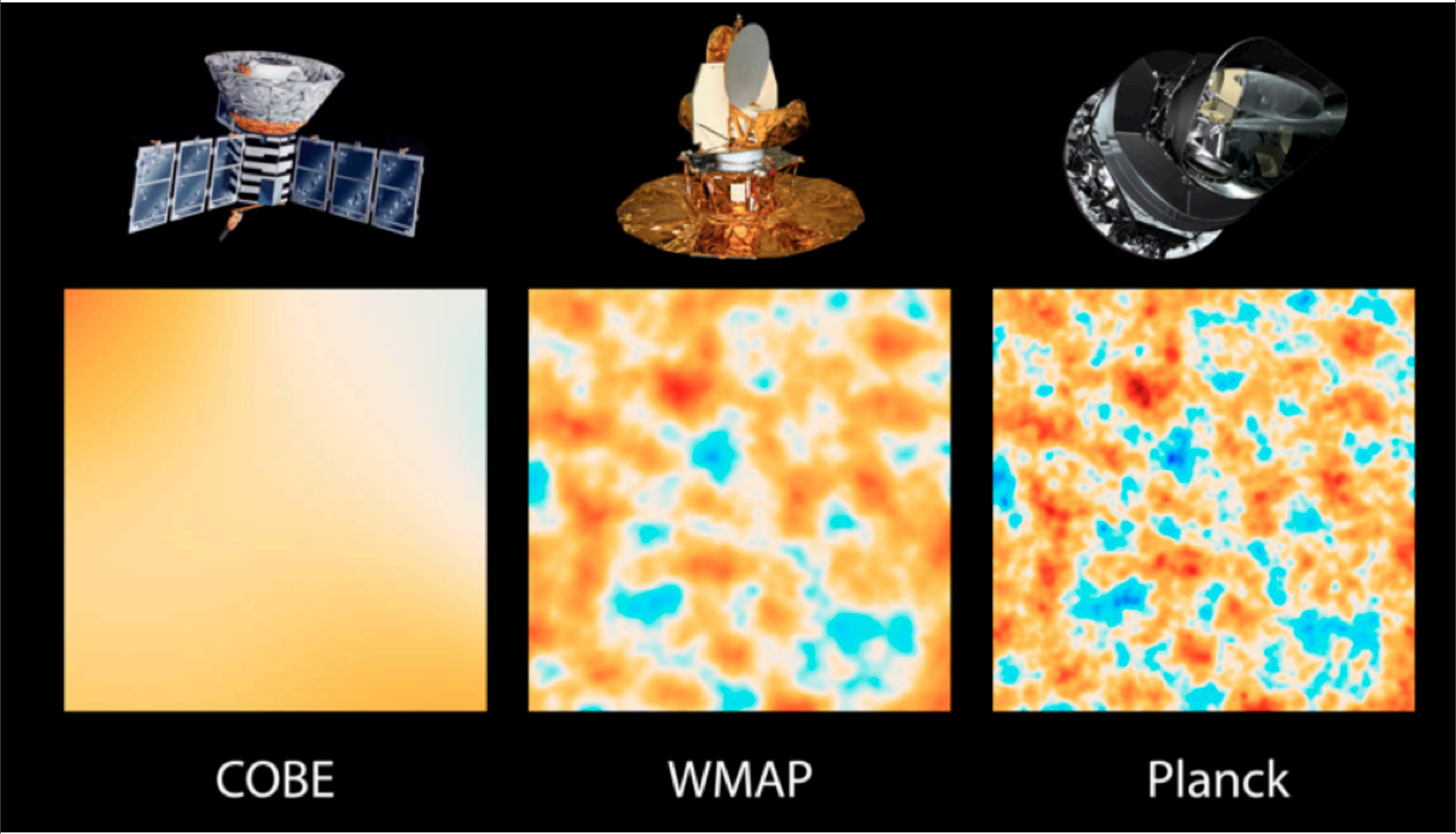
dipole: 3 mK, from motion of Earth



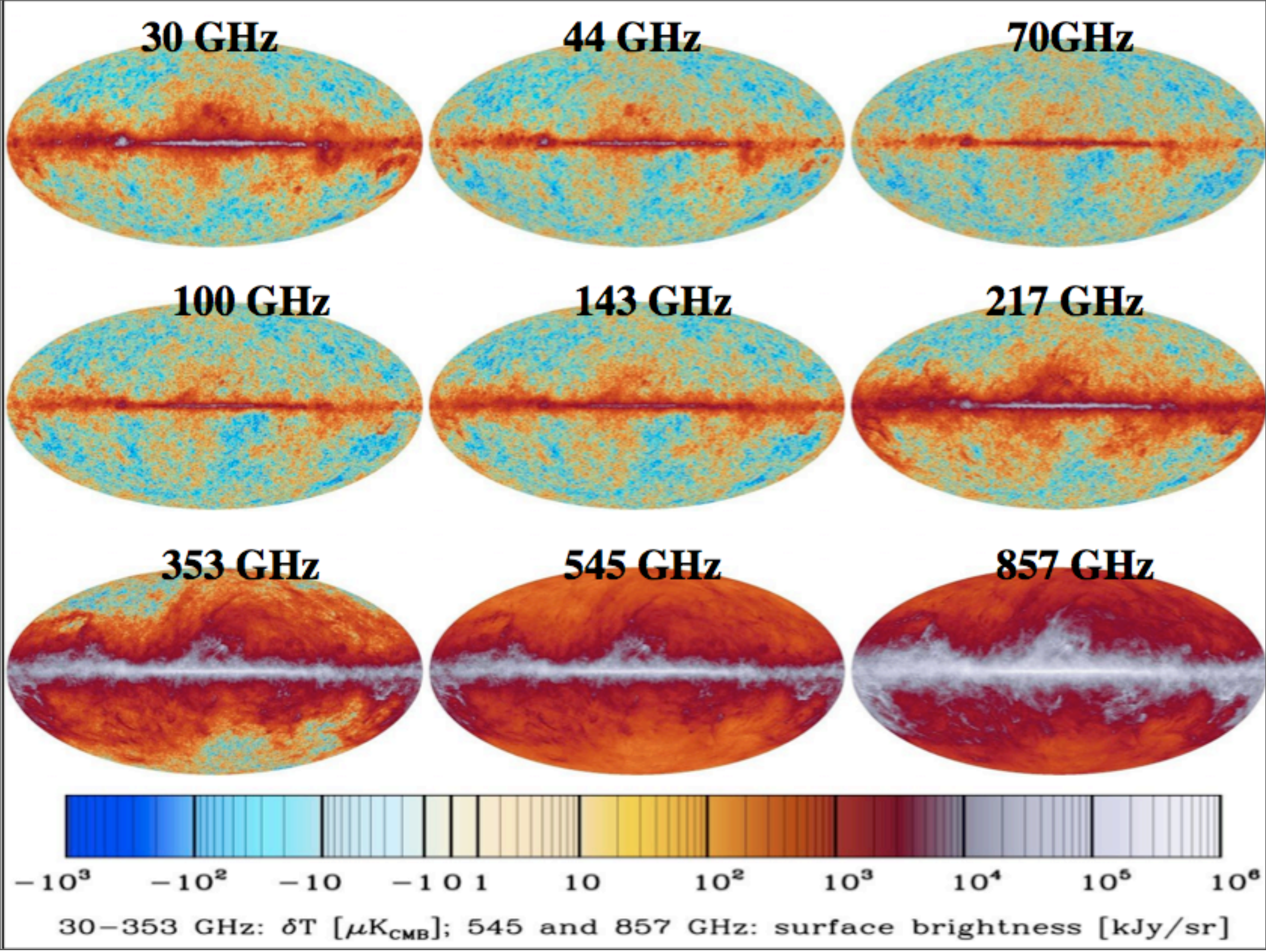


higher anisotropy: 100 μK, "snapshot of universe at z=1100"

Planck

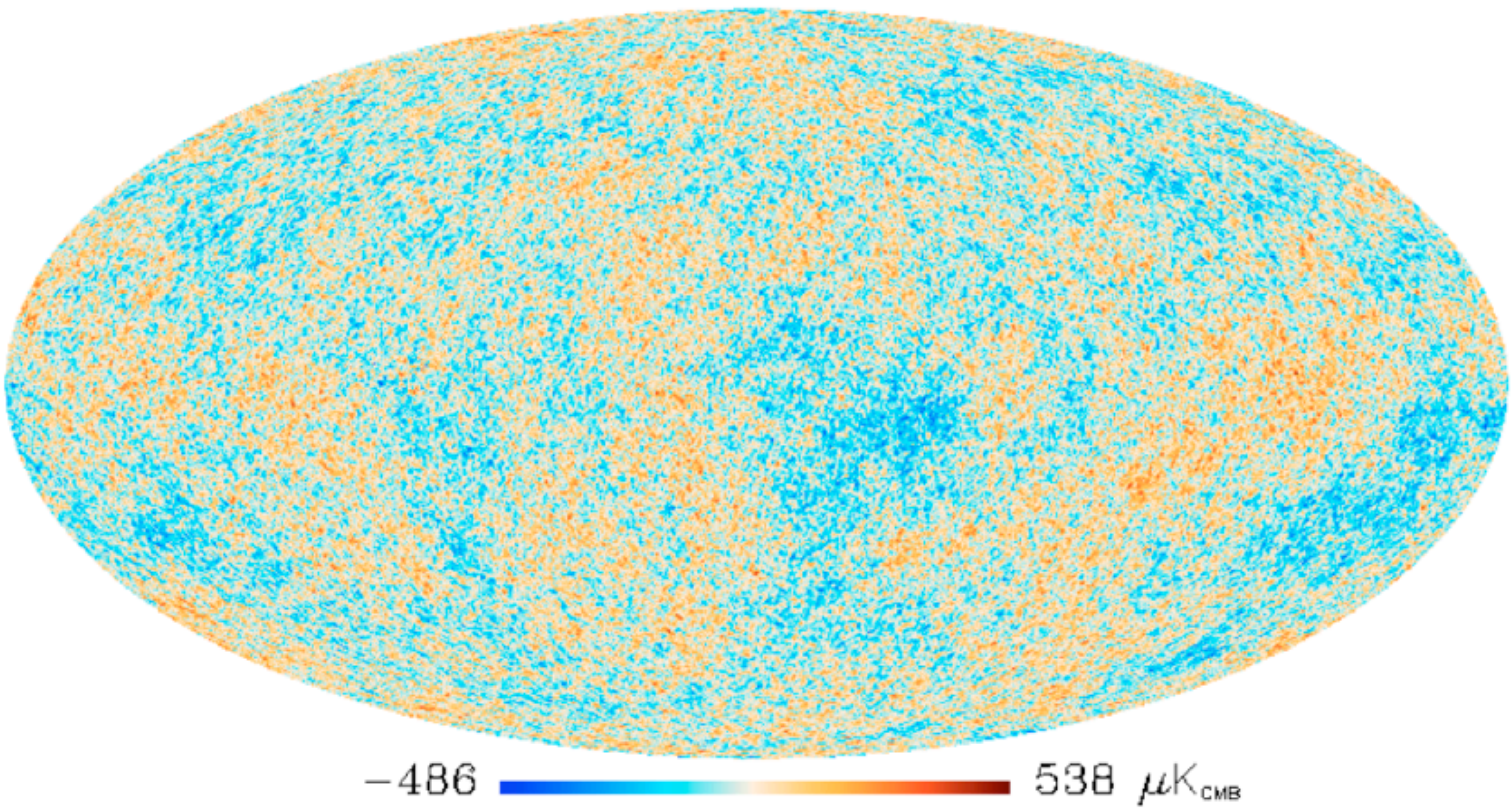


First data release: ~50% of the total data, no polarization



30 GHz
44 GHz
70GHz
100 GHz
143 GHz
217 GHz
353 GHz
545 GHz
857 GHz
-10^3 -10^2 -10 -1 0 1 10 10^2 10^3 10^4 10^5 10^6
30–353 GHz: δT [μK_{CMB}]; 545 and 857 GHz: surface brightness [kJy/sr]

Foreground cleaned CMB map



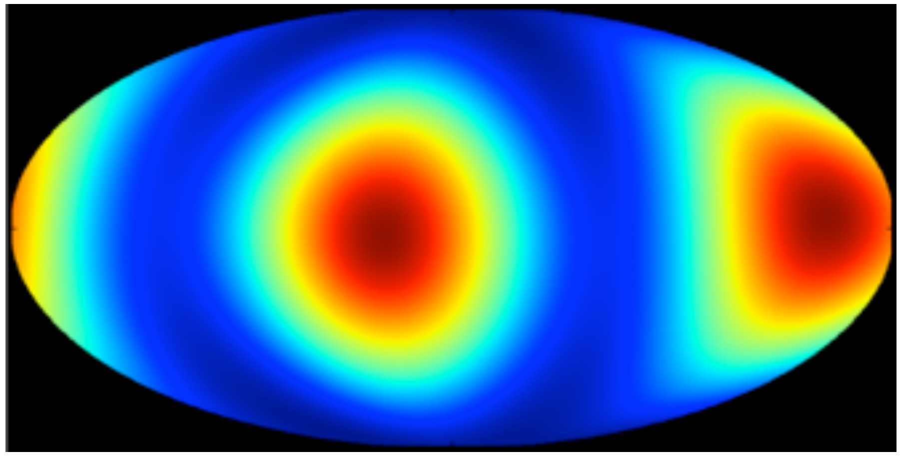
Spherical harmonic representation

Represent full-sky temperature in spherical harmonic basis:

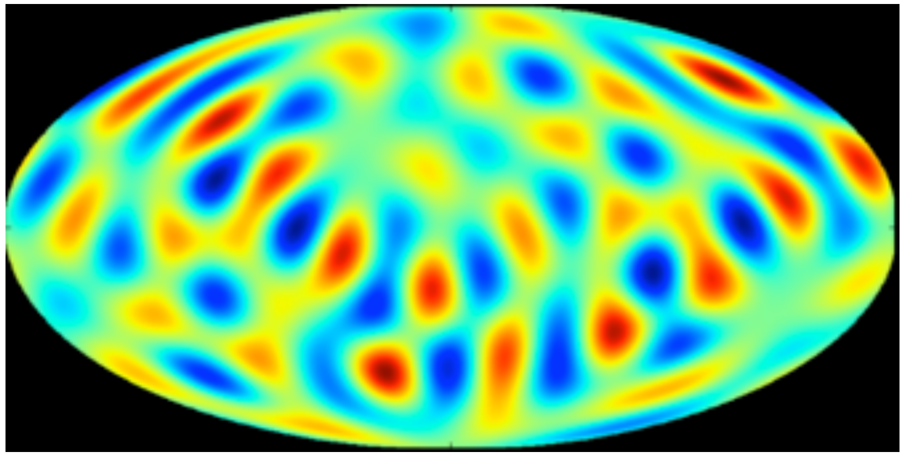
$$\Delta T(\theta,\phi) = \sum_{\ell=2}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\theta,\phi)$$

$(\Delta T) \rightarrow a_{\ell m}$ is analog of Fourier transform on the sphere

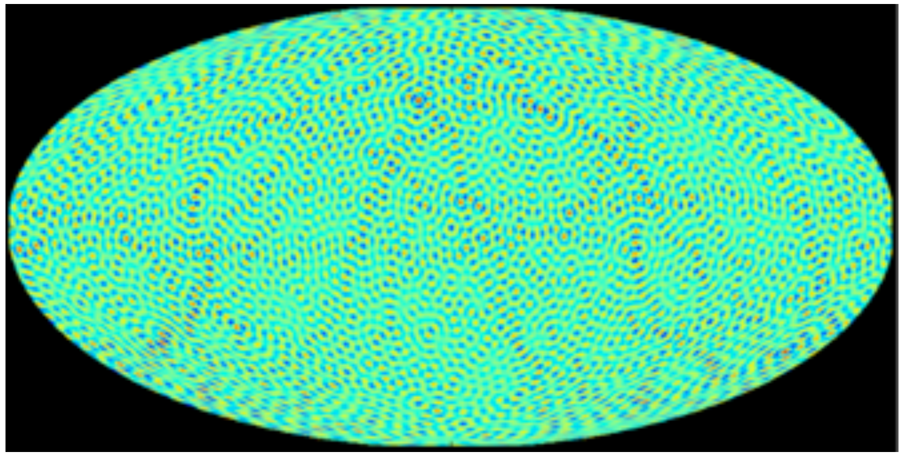
ℓ = "wavelengths per 360 degrees on sky"



$\ell = 2$



$\ell = 10$



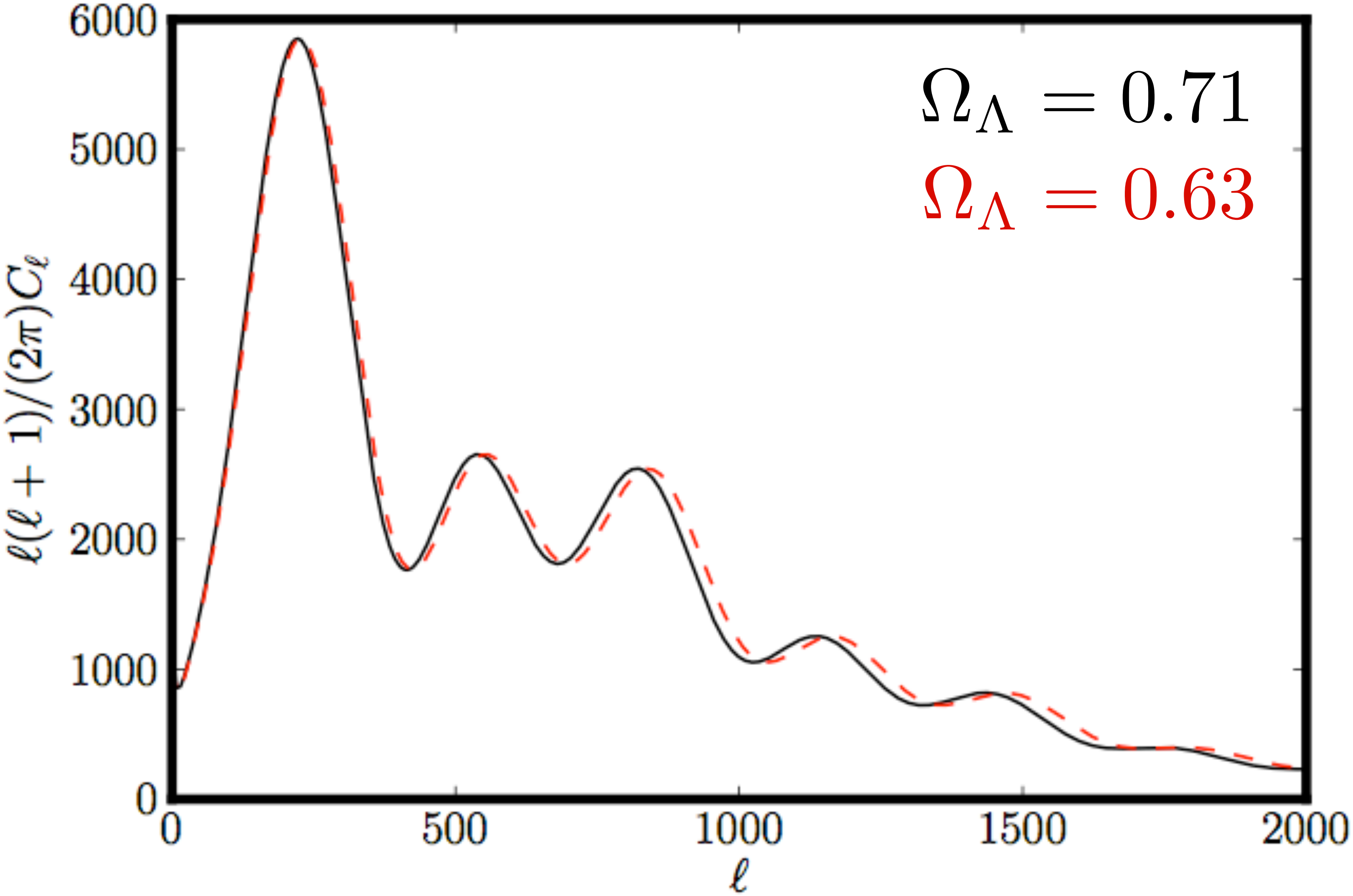
$\ell = 100$

Power spectrum

Standard cosmological model predicts: each $a_{\ell m}$ is an independent Gaussian random variable with ℓ-dependent variance

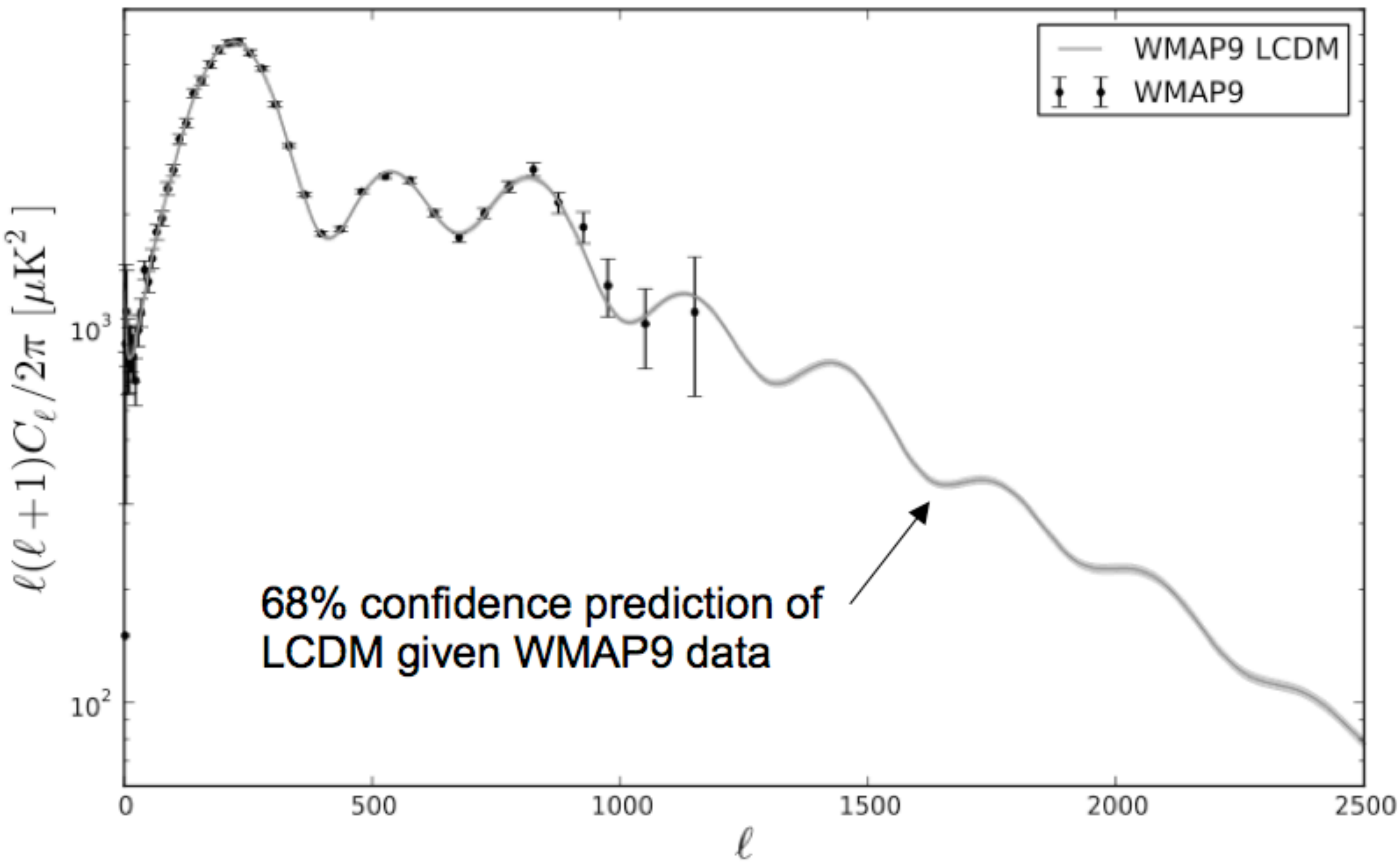
$$\langle a_{\ell m} a^*_{\ell' m'} \rangle = C_\ell \, \delta_{\ell \ell'} \delta_{m m'}$$

The power spectrum C_ℓ depends on cosmological parameters



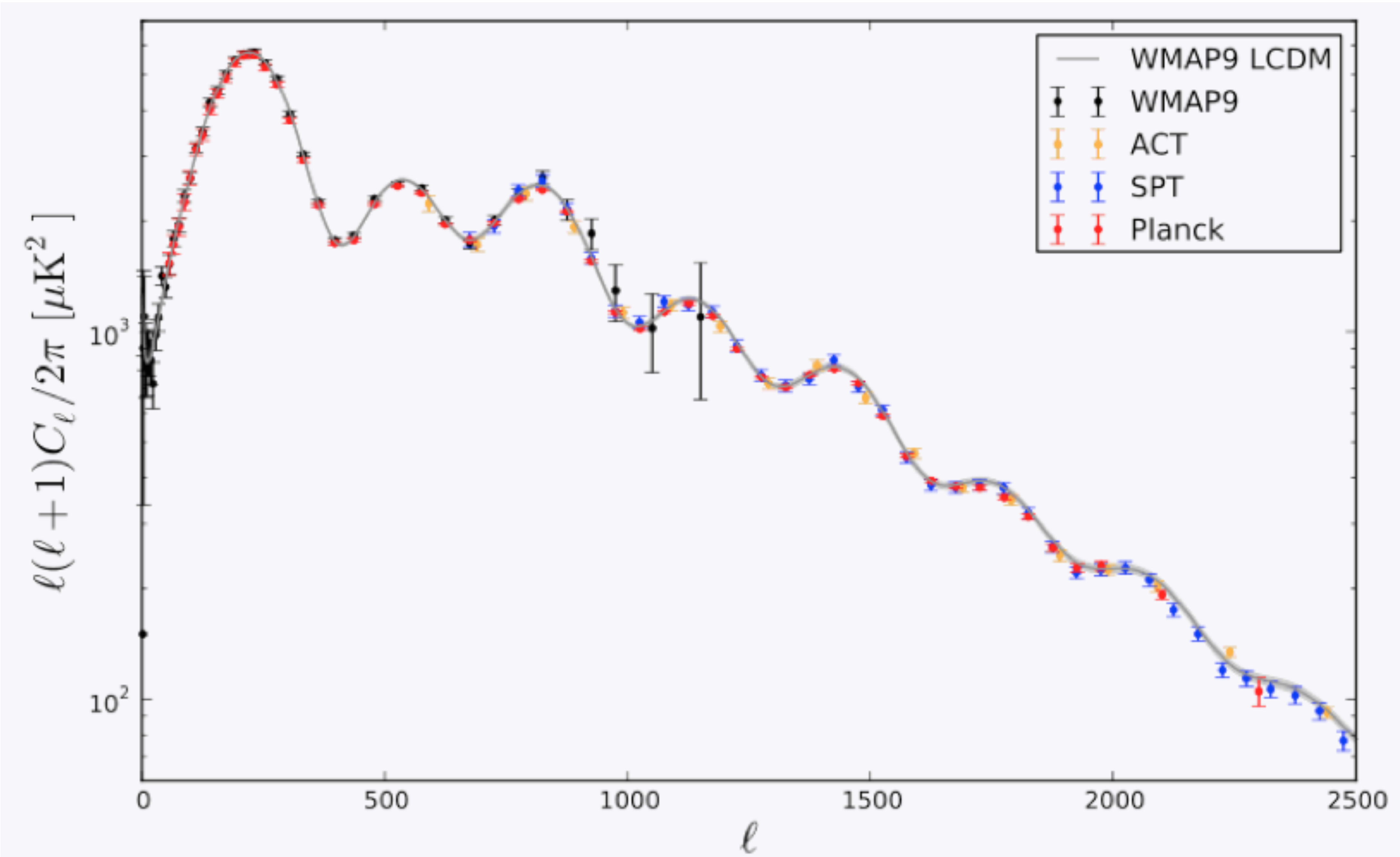
Power spectrum

Main goal of Planck: test prediction of the standard model

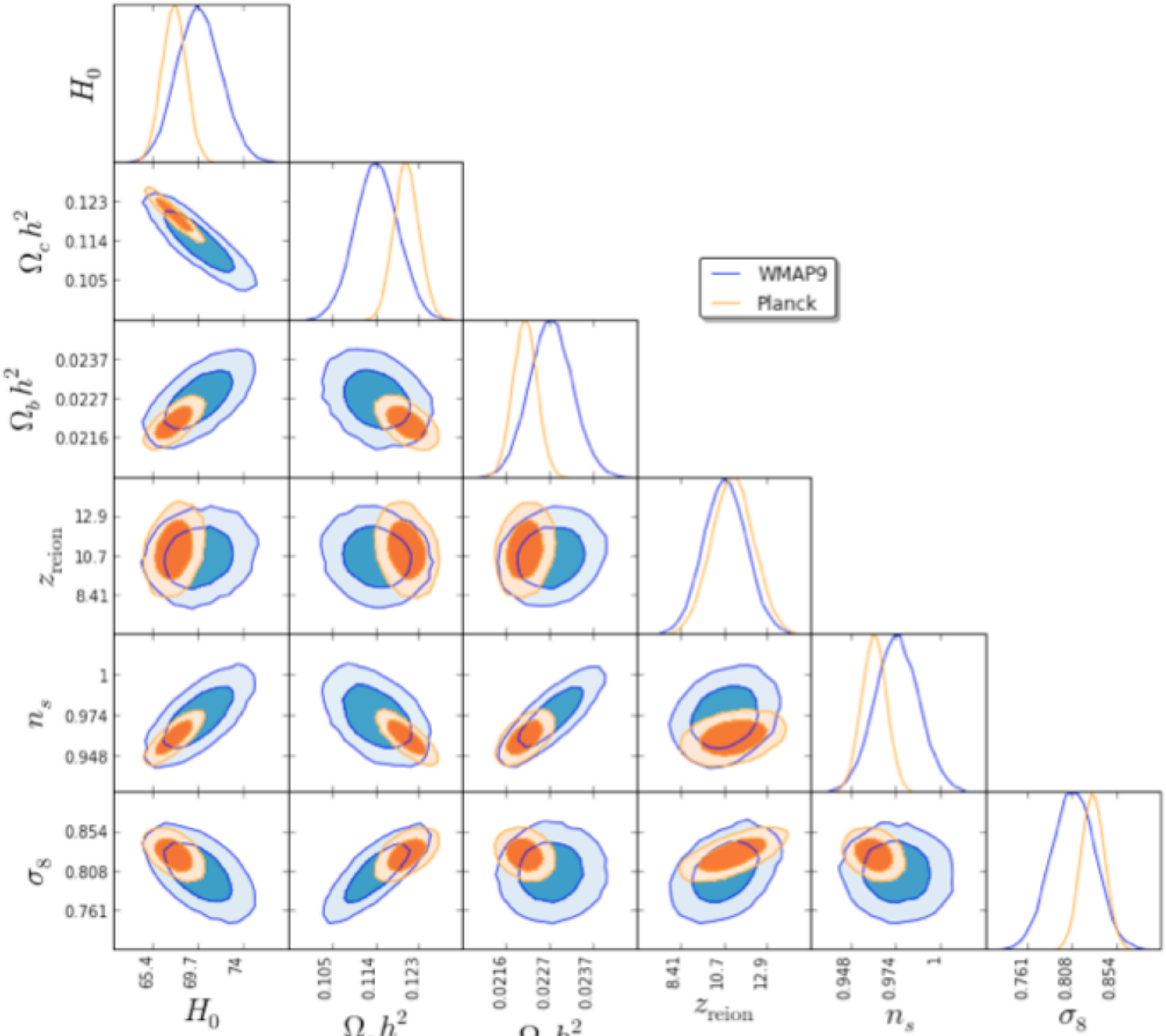


Power spectrum

Main result: Planck's measurement of the power spectrum is fully consistent with the standard model



Standard model constraints



Deviations from standard model

Some 1-parameter extensions to the standard model

In all cases, the 95% confidence region includes the SM value

Curvature	$-0.0071 < \Omega_K < 0.0060$
Neutrino mass	$\sum m_\nu < 0.230\ \mathrm{eV}$
No. of neutrino species	$2.79 < N_{\mathrm{eff}} < 3.84$
Primordial gravity waves	$r < 0.111$
Running spectral index	$-0.031 < dn_s/(d\log k) < 0.002$
Dark energy equation of state	$-1.38 < w < -0.90$
Primordial non-Gaussianity	$-8.9 < f_{NL}^{\mathrm{loc}} < 14.3$ $-192 < f_{NL}^{\mathrm{equil}} < 108$ $-103 < f_{NL}^{\mathrm{ortho}} < 53$

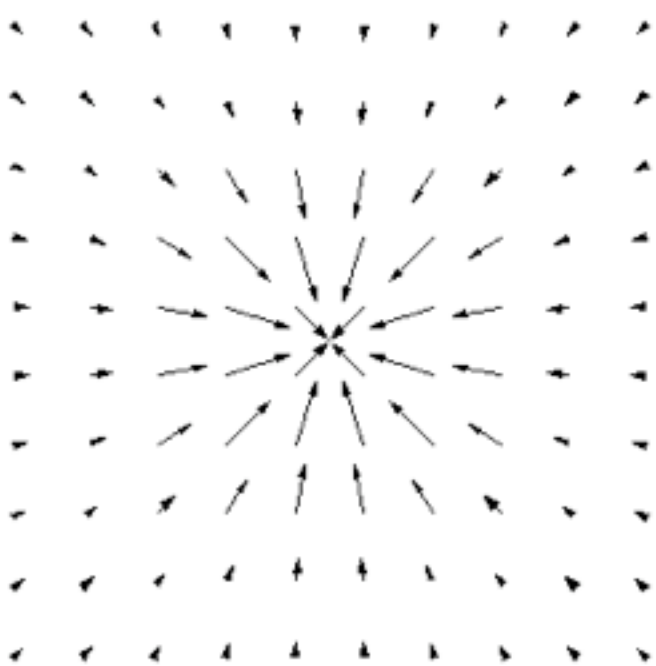
1. Gravitational lensing

2. Inflation

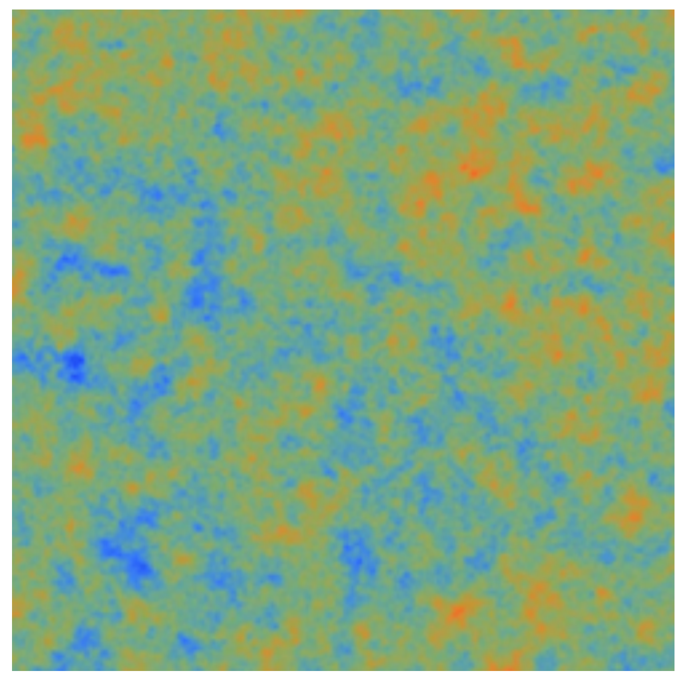
3. Tension with standard model, or with other experiments

Gravitational lensing

Apparent locations of CMB hot and cold spots are deflected by intervening large scale structure

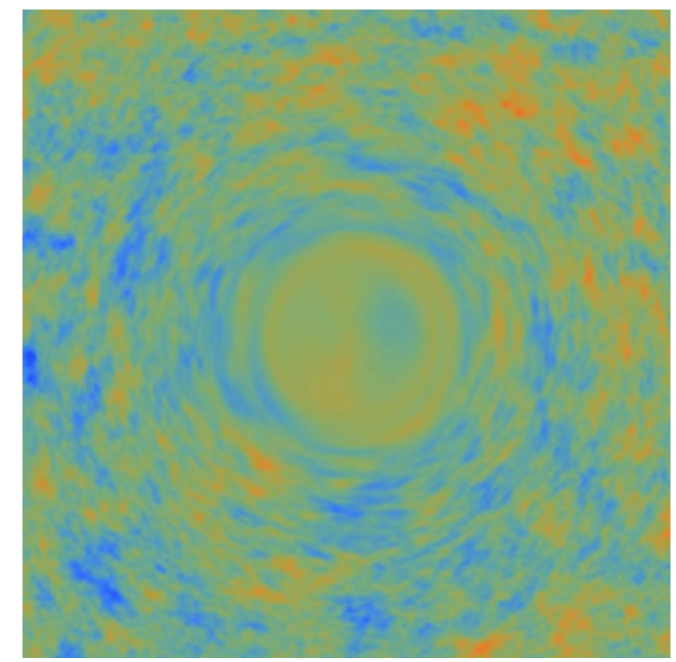


Deflection angles



Unlensed CMB

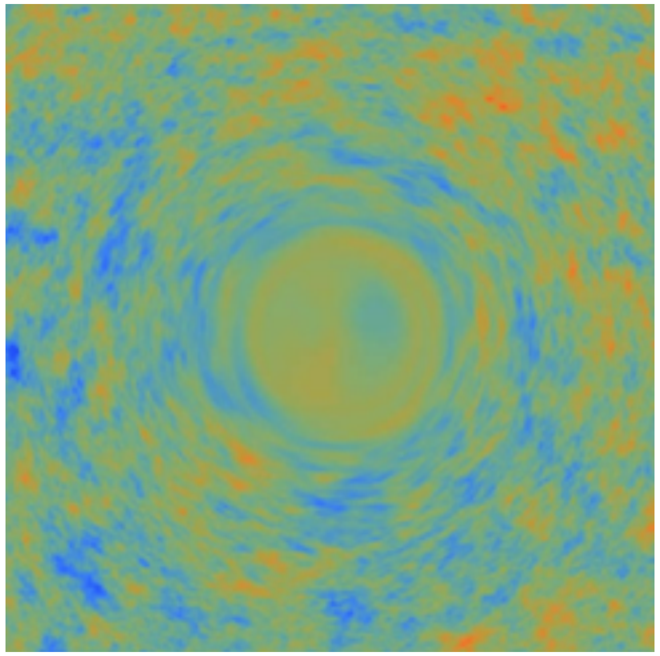
(exaggerated)



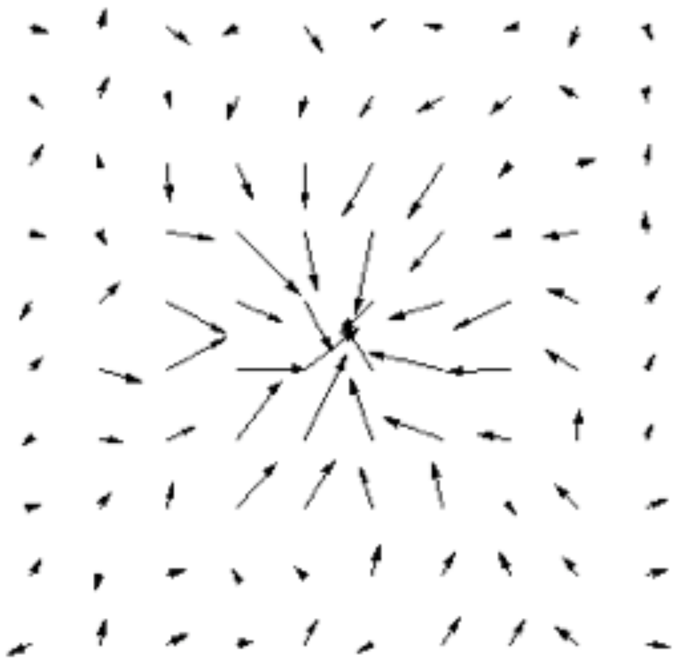
Lensed CMB

“Lens reconstruction”

Intuitive idea: from lensed noisy CMB, reconstruct deflection angles, with statistical noise



Lensed CMB

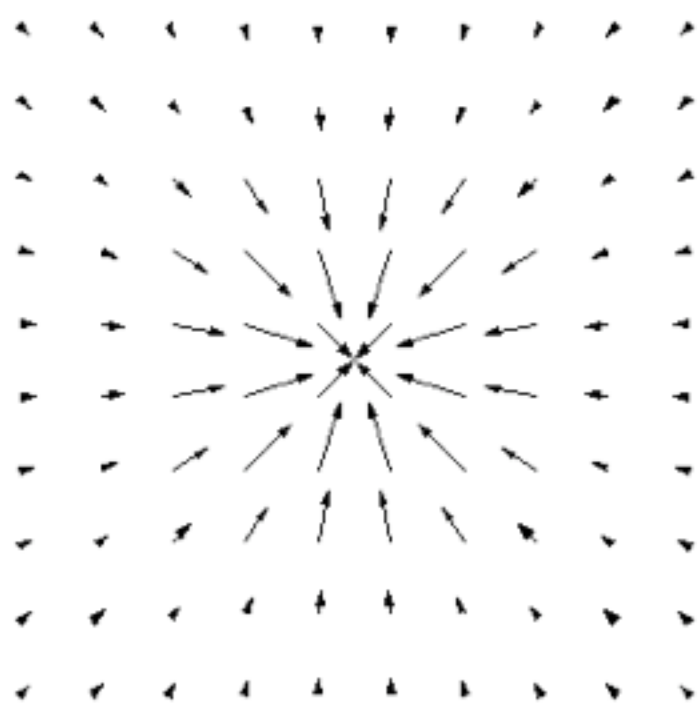


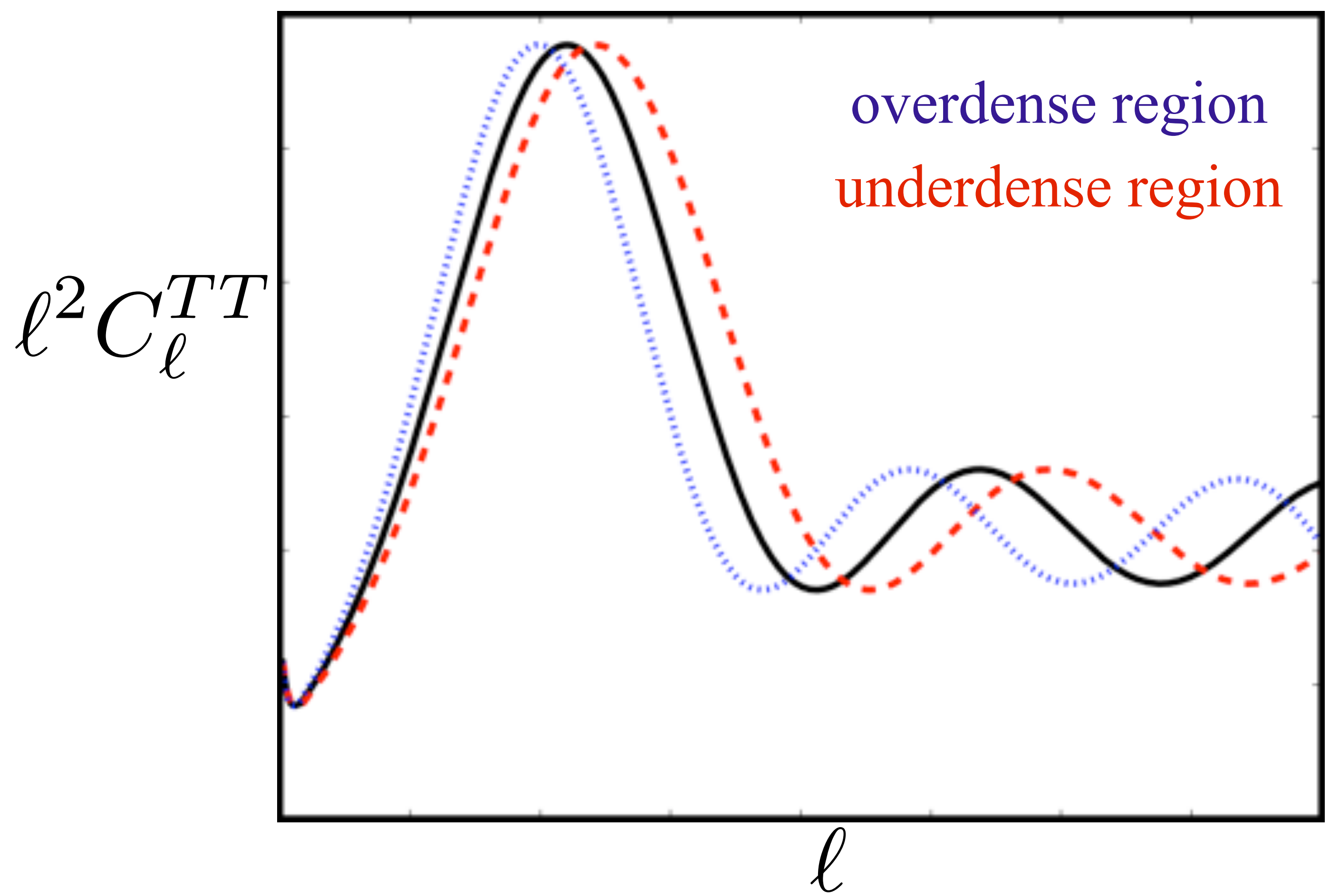
Lens reconstruction + noise

Lens reconstruction

Consider a large (~10 deg) overdense region

CMB appears slightly magnified; acoustic peaks move to lower l

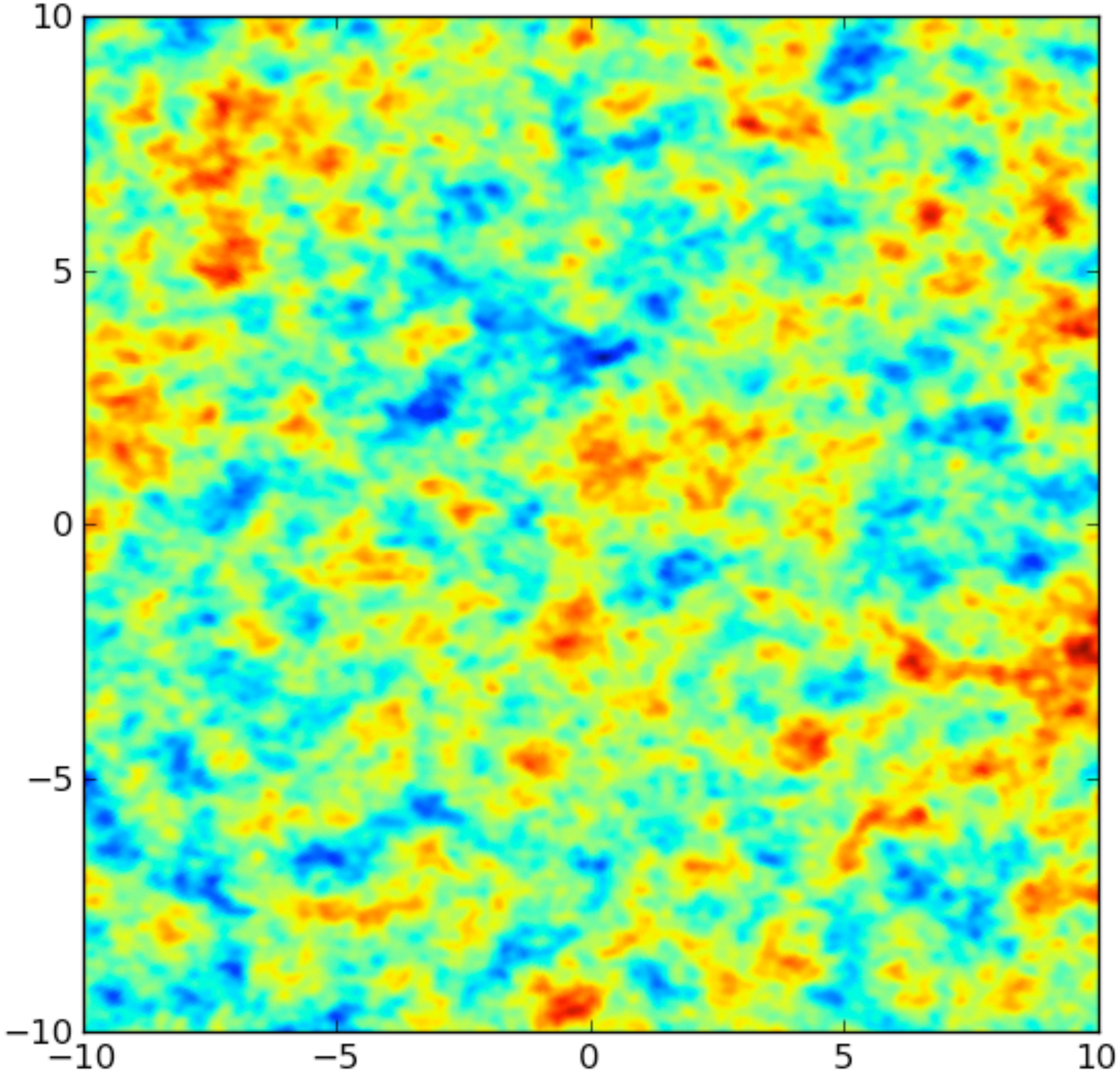




Leads to quadratic estimator for each Fourier mode of the lenses

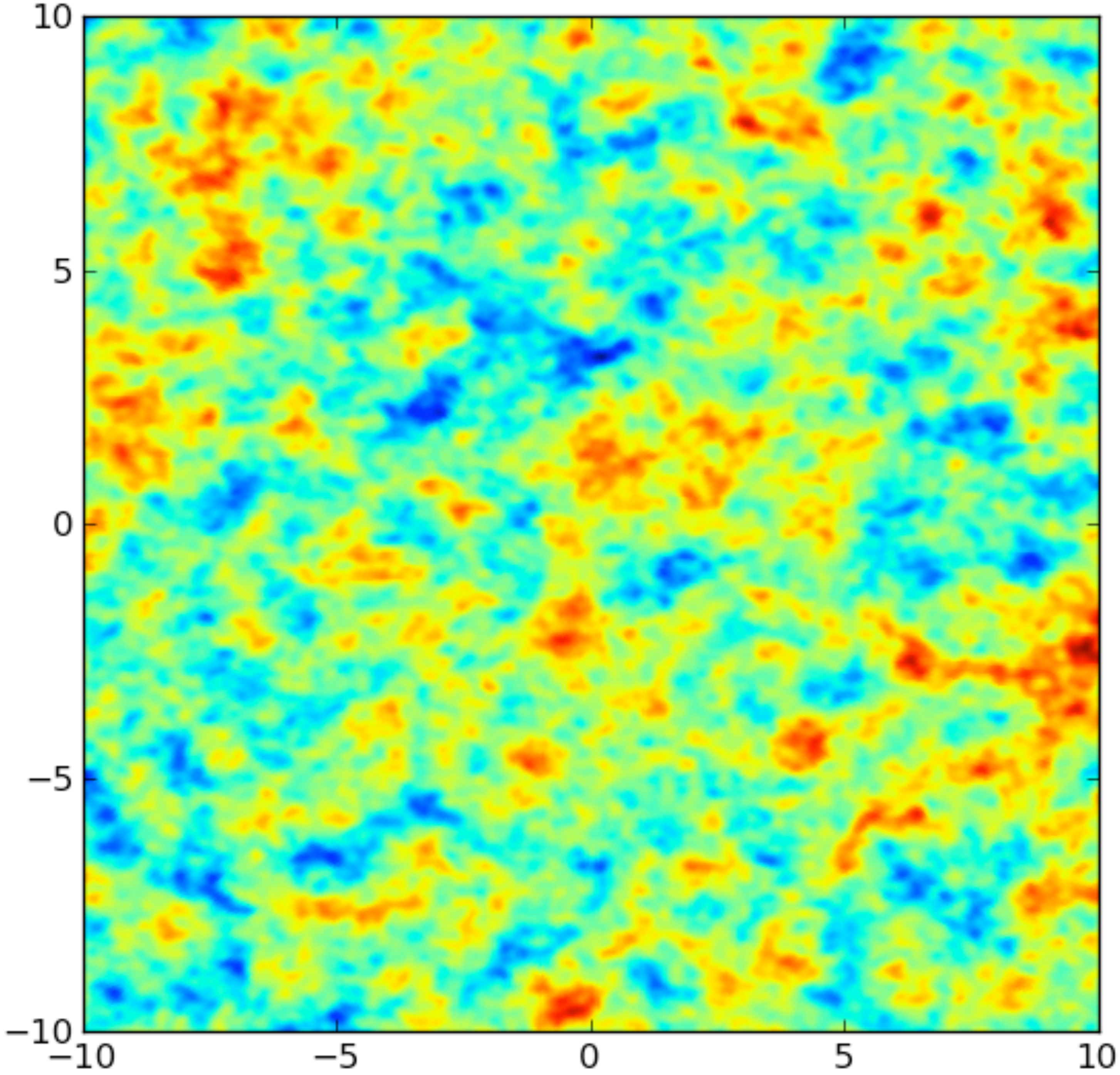
$$d_{\mathbf{l}} = \int \frac{d^2\mathbf{l}'}{(2\pi)^2} W_{\mathbf{l}\mathbf{l}'\mathbf{l}''} T_{\mathbf{l}'} T_{\mathbf{l}-\mathbf{l}'}$$

Unlensed CMB



Duncan Hanson

Lensed CMB



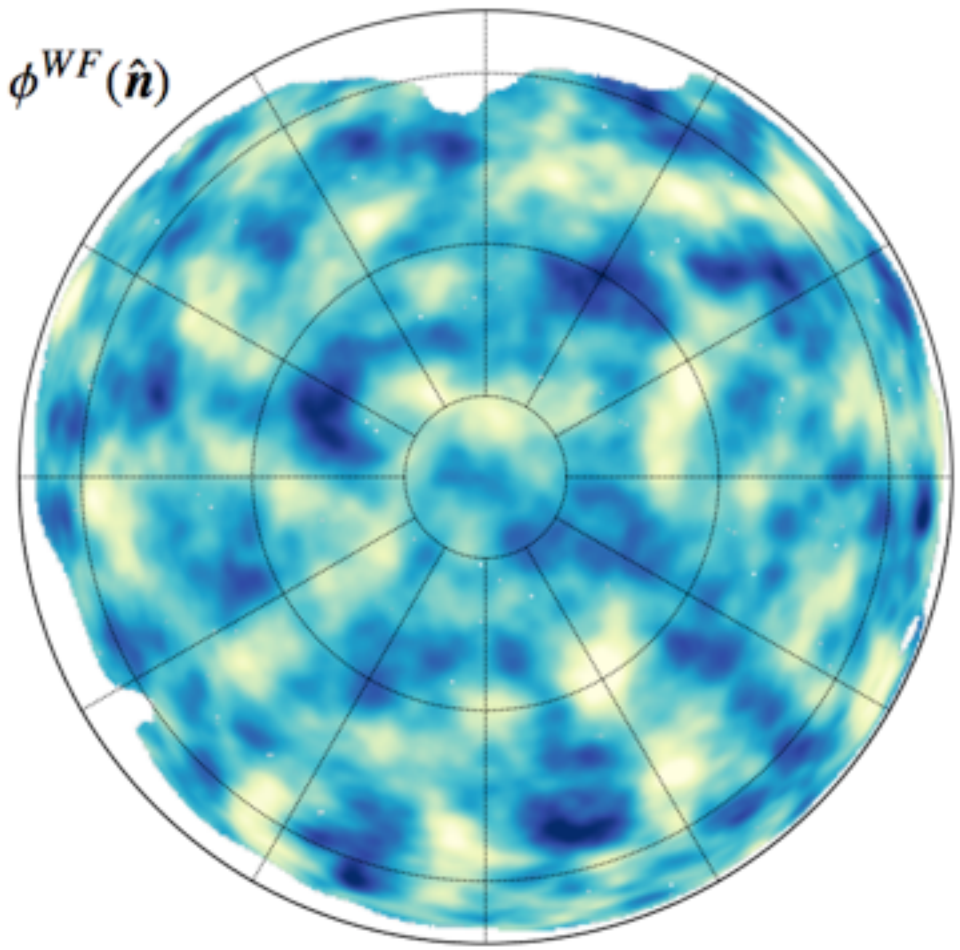
Typical lensing deflection: ~2 arcmin
Typical lens size: ~few degrees

Duncan Hanson

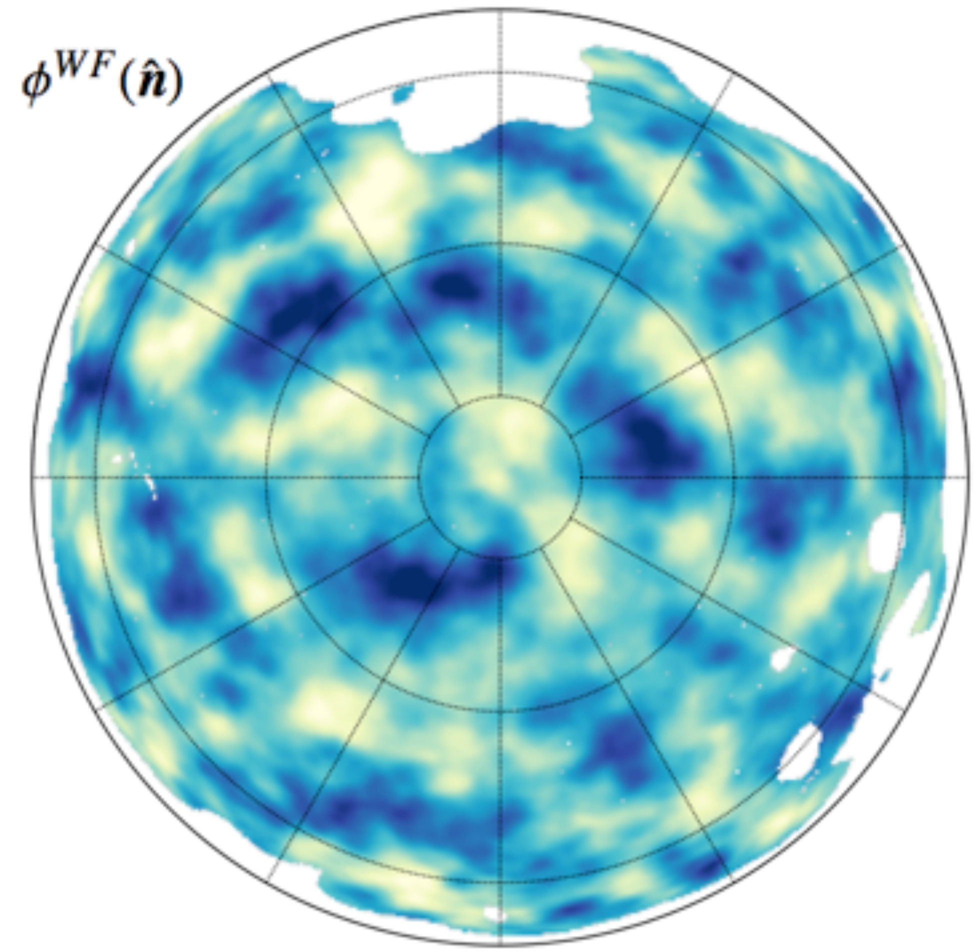
Planck lensing: results

Maps of lensing potential ϕ (deflection field is $\vec{d} = \vec{\nabla}\phi$)

Statistical noise is a factor ~few larger than the ϕ fluctuations



Galactic North



Galactic South

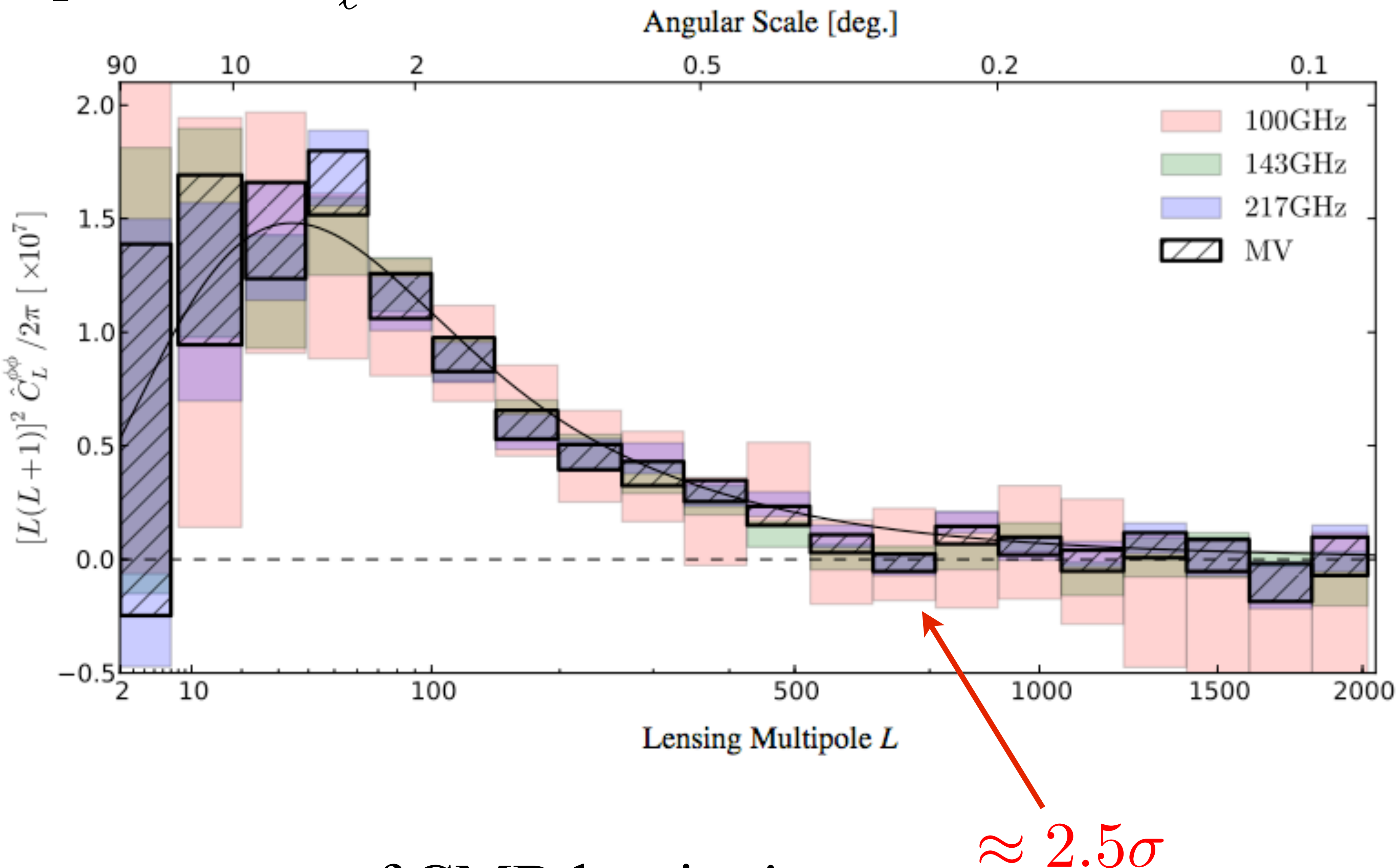
Line-of-sight integral: $\phi(\mathbf{n}) = -2\int dr \left(\frac{r_{\mathrm{CMB}} - r}{r_{\mathrm{CMB}}\, r}\right) \Psi(r\mathbf{n}, r)$

peaks at z~2

Newtonian potential

Planck lensing: results

Power spectrum $C_\ell^{\phi\phi}$



25σ measurement of CMB lensing!

(Previous measurements: ACT ~4σ, SPT ~6σ)

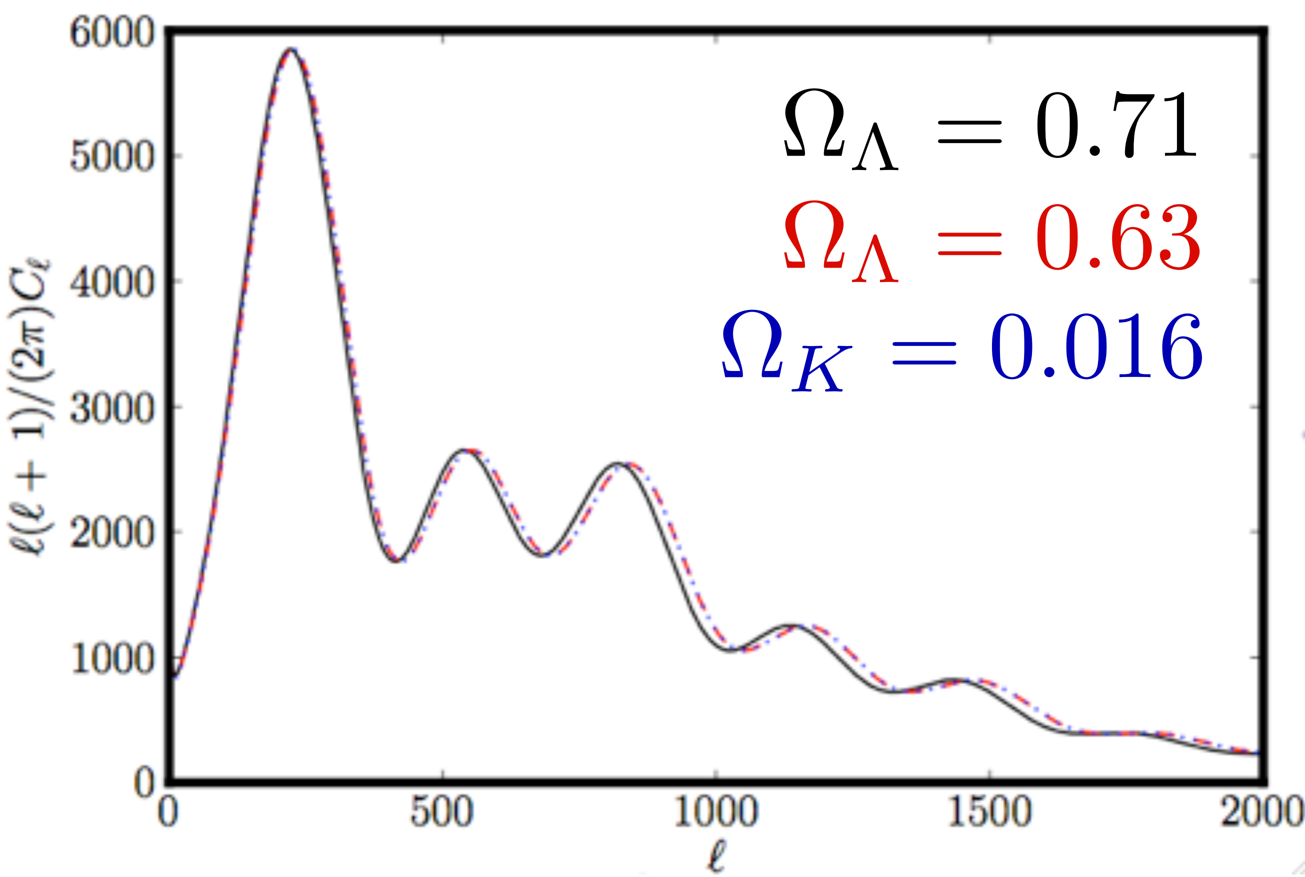
We can now do precision cosmology with CMB lensing...

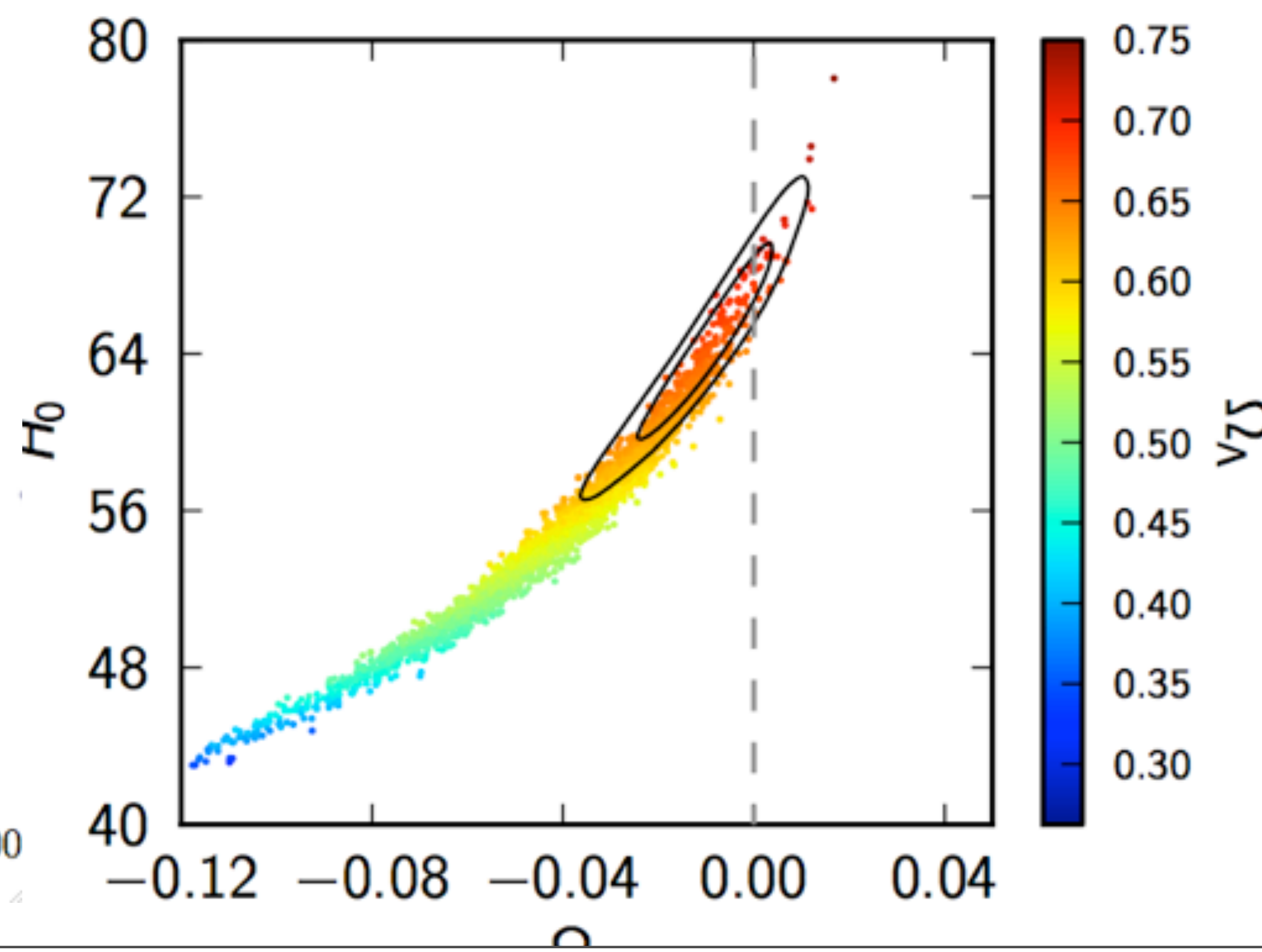
Planck lensing: results

Example: Planck measurement of curvature Ω_K

In the unlensed CMB, varying either Ω_K or Ω_Λ mainly changes the angular scale of the acoustic peaks, leading to a degeneracy

CMB lensing breaks the degeneracy, allowing both Ω_K and Ω_Λ to be determined





1. Gravitational lensing

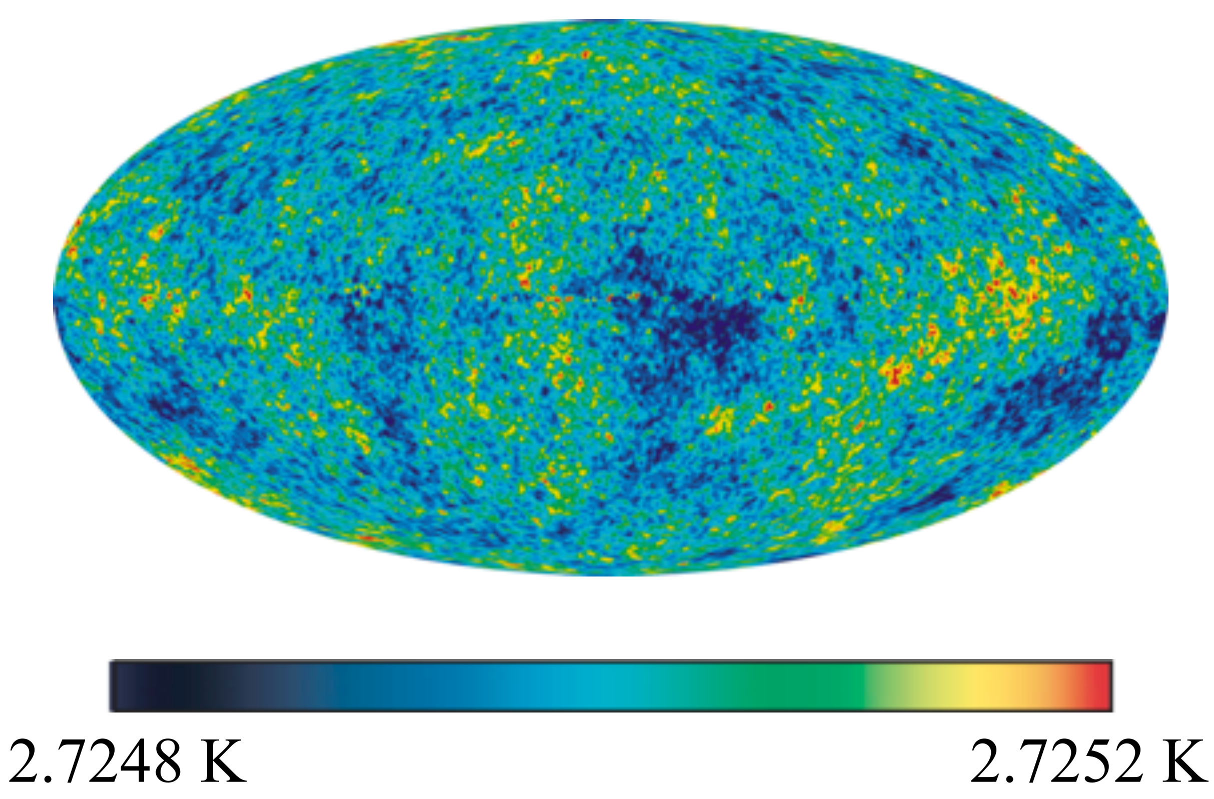
2. Inflation

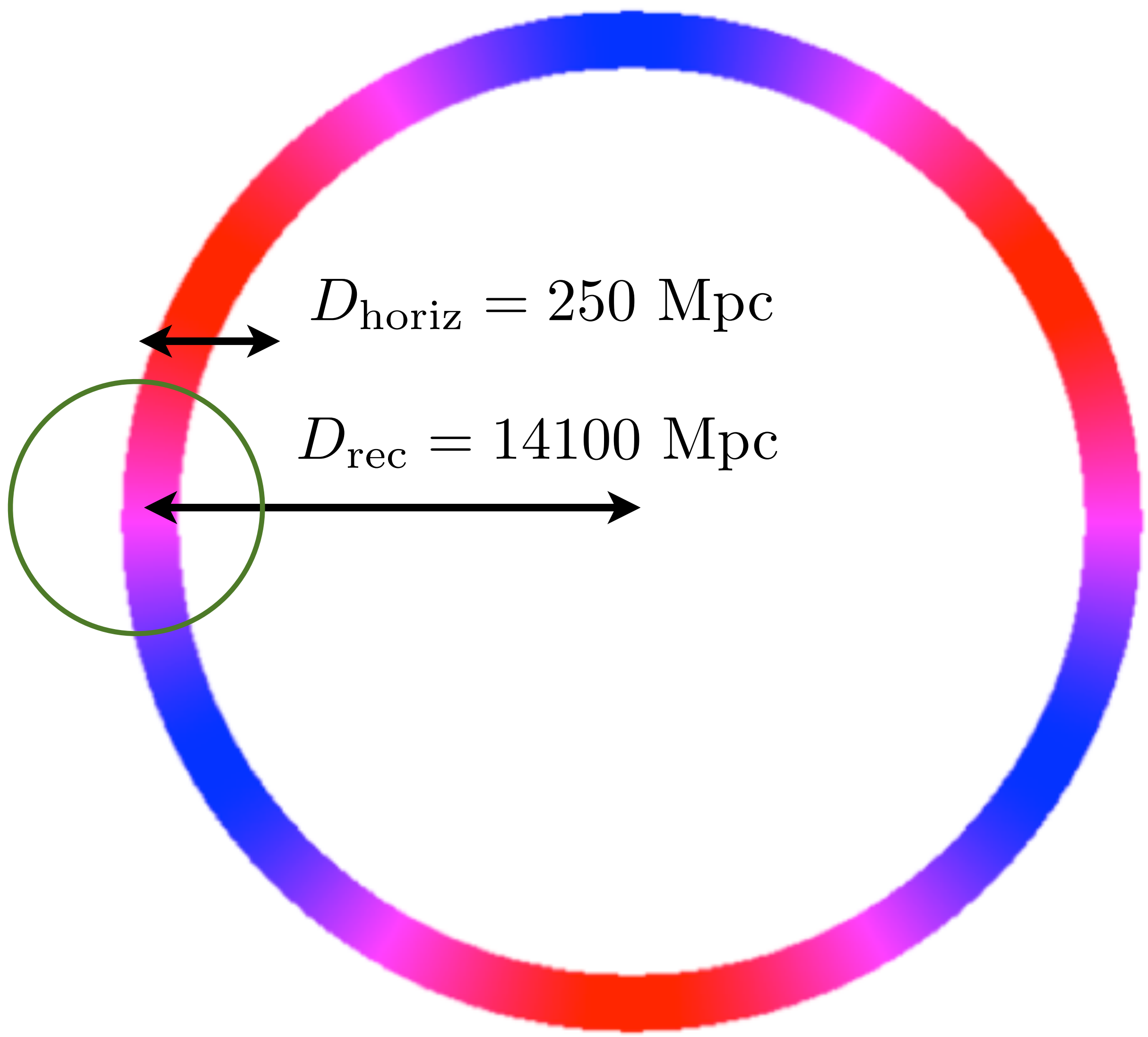
3. Tension with standard model, or other experiments

Inflation: horizon problem

Surface of last scattering is nearly isothermal, suggesting that all parts of the last scattering surface were once in causal contact

However, the causal horizon at last scattering is much smaller: points separated by $> 1^\circ$ have never been in causal contact





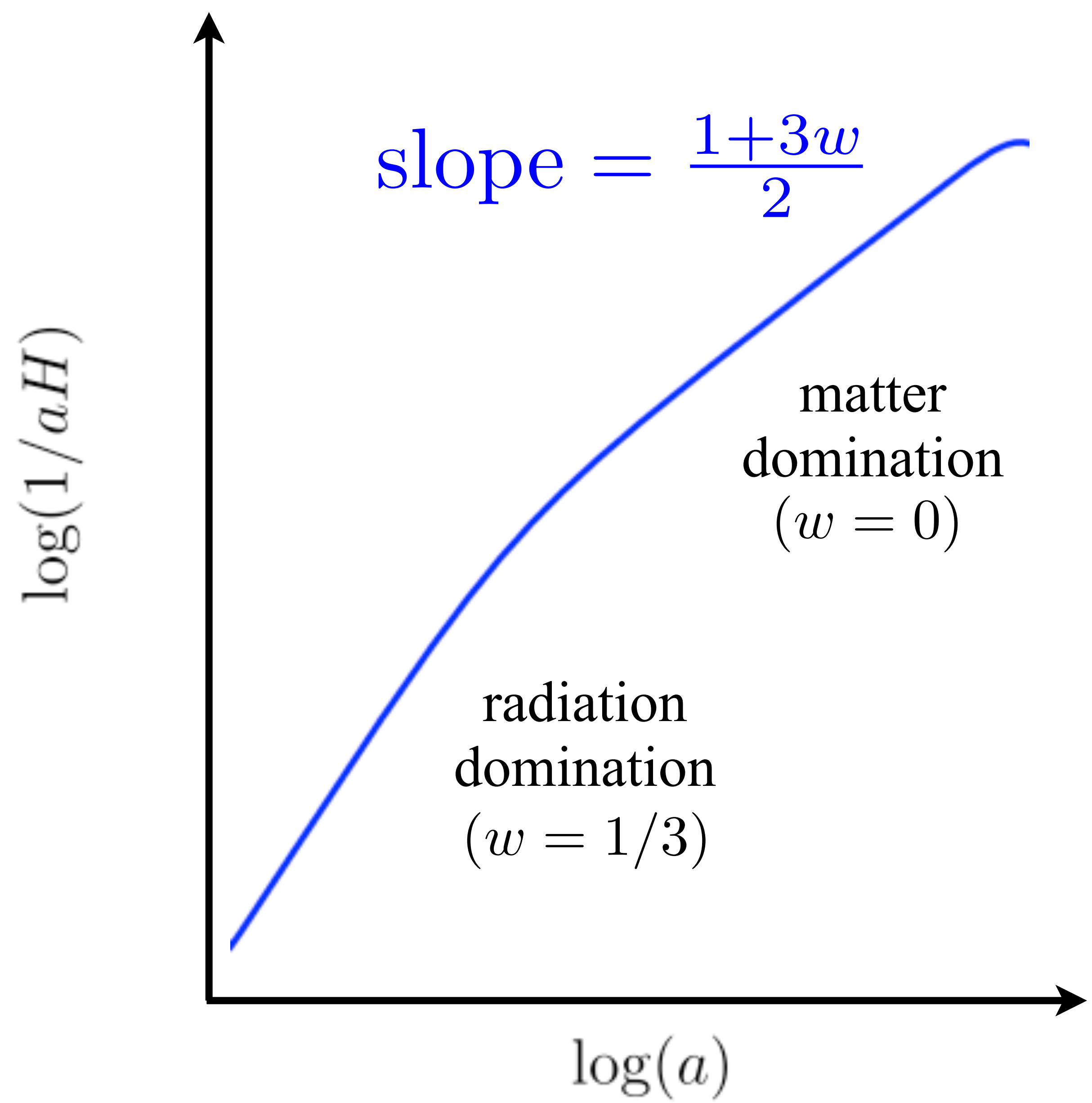
Inflation: horizon problem

$(aH)^{-1} =$ comoving distance light travels in an e-folding

Evolution with scale factor a:

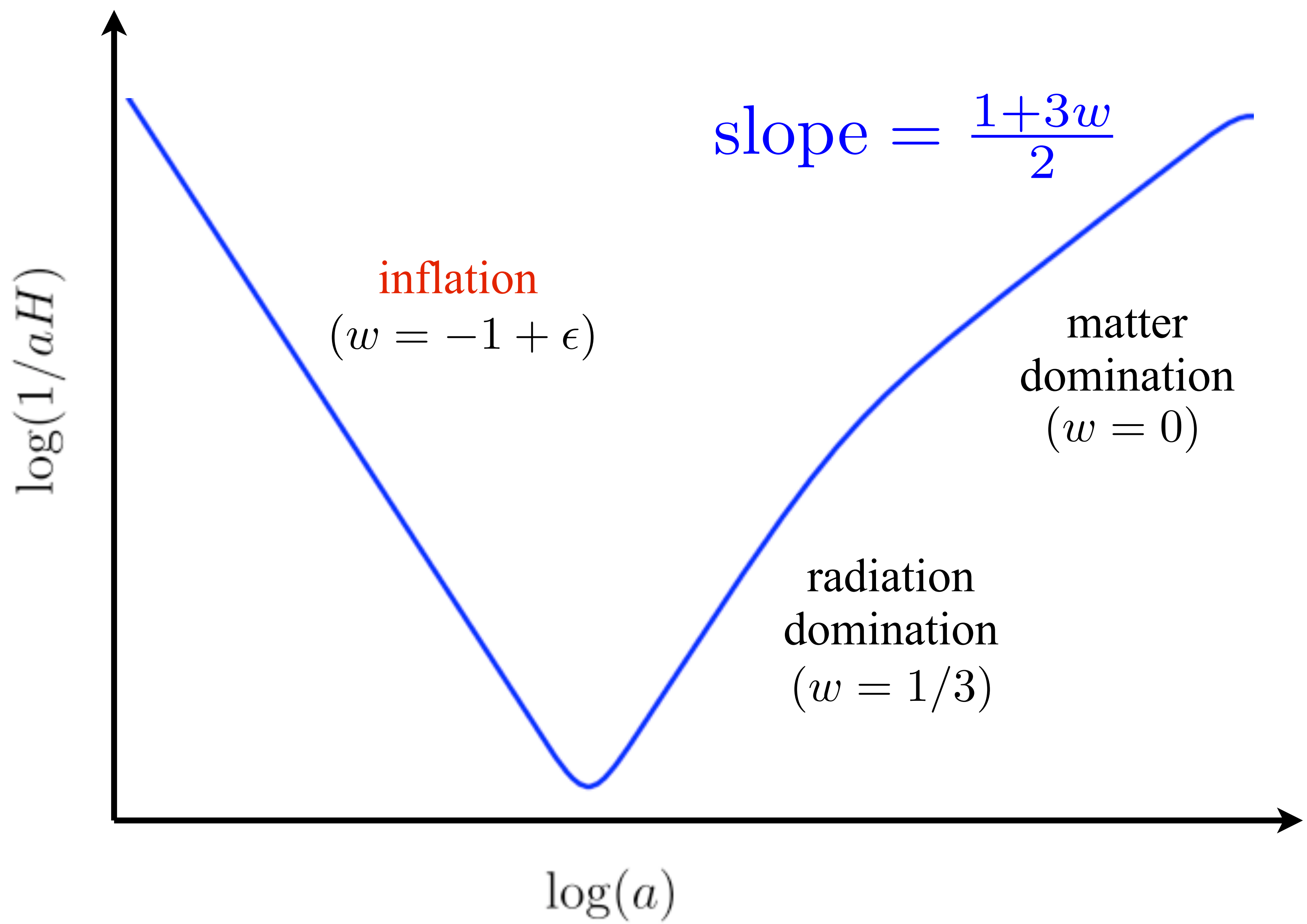
$$\frac{d\log(aH)^{-1}}{d\log a} = \frac{1+3w}{2} \qquad \left(w = \frac{\text{pressure}}{\text{energy density}}\right)$$

In a universe filled with nonrelativistic $(w=0)$ or relativistic $(w=1/3)$ matter, the horizon is small at early times



Inflation: horizon problem

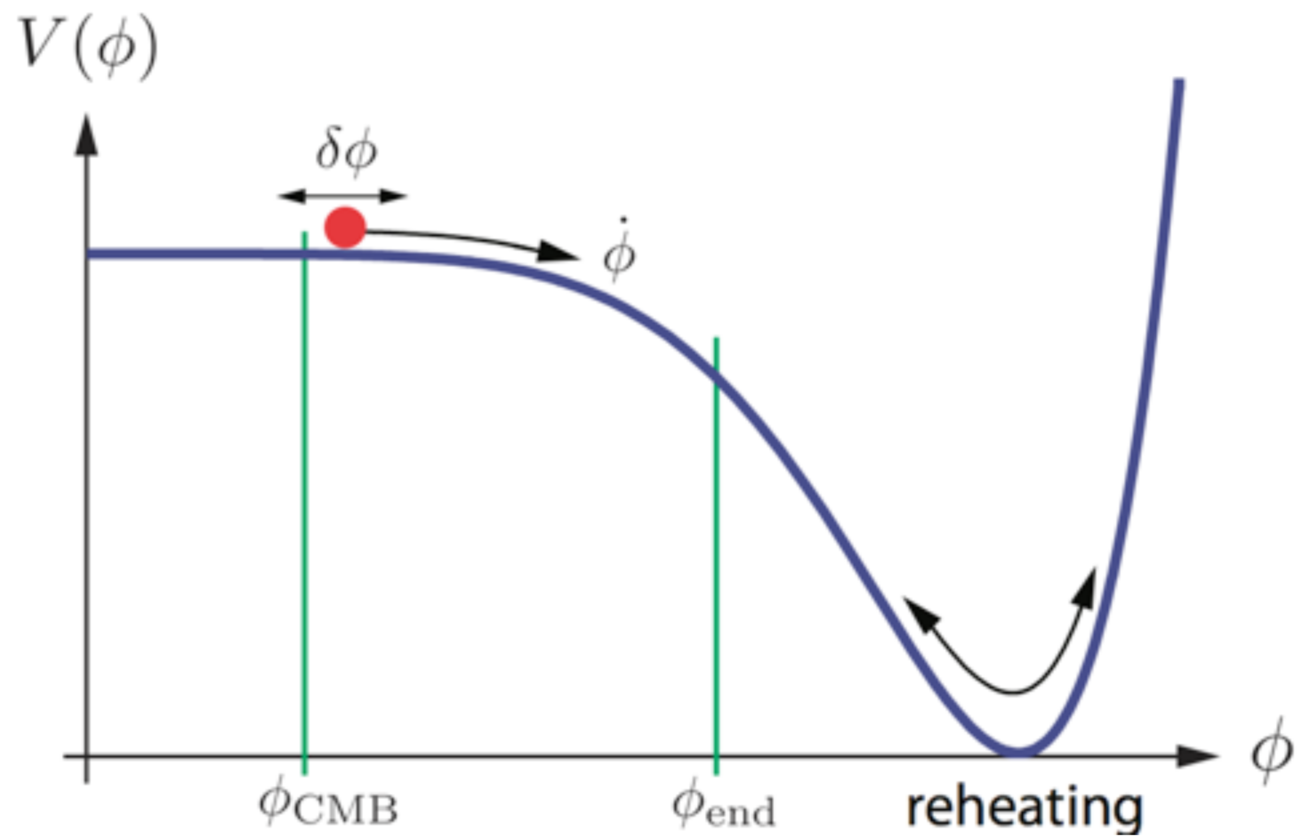
To get a large horizon at early times, ΛCDM expansion history must be preceded by an "inflationary" epoch with $w < -\frac{1}{3}$, i.e. negative pressure



Single-field slow-roll inflation

Example model: scalar field ϕ slowly rolling down potential $V(\phi)$

$$S = \int d^4x \sqrt{-g}\left(\frac{1}{2}(\partial\phi)^2 - V(\phi)\right)$$



Flatness: $\epsilon = \frac{M_{\rm Pl}^2}{2}\left(\frac{V'(\phi)}{V(\phi)}\right)^2 \ll 1$

Negative pressure: $w = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)} \approx -1 + \frac{2}{3}\epsilon$

Generation of perturbations

Amazing fact: inflation naturally generates perturbations; microscopic degrees of freedom are quantum mechanically excited

First consider toy example as follows...

Exponentially expanding spacetime (de Sitter)

$$ds^2 = -dt^2 + e^{2Ht}dx^2 \qquad (-\infty < t < \infty)$$
$$= \frac{1}{(H\tau)^2}(-d\tau^2 + dx^2) \qquad (-\infty < \tau < 0)$$

Minimally coupled massless test scalar field

$$S = -\frac{1}{2}\int d^4x\,\sqrt{-g}\,g^{\mu\nu}(\partial_\mu\sigma)(\partial_\nu\sigma)$$
$$= \frac{1}{2}\int d\tau\,d^3x\,\frac{1}{(H\tau)^2}\left[\left(\frac{\partial\sigma}{\partial\tau}\right)^2 - (\partial_i\sigma)^2\right]$$

Generation of perturbations

Each Fourier mode $\sigma_{\mathbf{k}}$ behaves as a 1D harmonic oscillator with time dependent Hamiltonian

$$\widehat{H} = \frac{1}{2}\left[\frac{k^2}{(H\tau)^2}\hat{x}^2 + (H\tau)^2\hat{p}^2\right]$$

Schrodinger equation $i\frac{\partial\psi}{\partial\tau} = \hat{H}\psi$ is exactly solvable:

$$\psi(x,\tau) \propto \frac{1}{(1-ik\tau)^{1/2}} \underbrace{e^{-i\frac{k\tau}{2}-i\frac{k^2x^2}{2H^2\tau(1+k^2\tau^2)}}}_{\text{phase}} \underbrace{\exp\left(-\frac{k^3x^2}{2H^2(1+k^2\tau^2)}\right)}_{\text{Gaussian}}$$

Early-time limit $(\tau \ll -1/k)$: system stays in ground state (adiabatic)

$$\psi(x,\tau) \to \psi_{\rm ground}(x,\tau) \propto \exp\left(-\frac{kx^2}{2H^2\tau^2}\right)$$

Late-time limit $(\tau \gg -1/k)$: wavefunction "frozen" to constant value

$$\psi(x,\tau) \to \exp\left(-\frac{k^3x^2}{2H^2}\right)$$

Generation of perturbations

Toy model, conclusion: In the late-time limit, each Fourier mode $\sigma_{\mathbf{k}}$ is an independent Gaussian with variance

$$\langle \sigma_{\mathbf{k}} \sigma^*_{\mathbf{k}'} \rangle = \frac{H^2}{2k^3} (2\pi)^3 \delta^3(\mathbf{k} - \mathbf{k}')$$

i.e. σ is a Gaussian random field with scale-invariant power spectrum

$$P(k) = \frac{H^2}{2k^3}$$

Generation of perturbations

Inflationary model: $S = \int d^4x \sqrt{-g} \left(-\frac{1}{2} g^{\mu\nu} (\partial_\mu \phi)(\partial_\nu \phi) - V(\phi) \right)$

[with dynamical $g_{\mu\nu}$]

"Scalar perturbations": at the end of inflation, the adiabatic curvature ζ is a Gaussian field with nearly scale-invariant power spectrum

$$P_\zeta(k) = A_\zeta \left(\frac{k}{k_0} \right)^{n_s - 4}$$

where $n_s - 1 = M_{\mathrm{Pl}}^2 \left[2 \frac{V''(\phi)}{V(\phi)} - 3 \left(\frac{V'(\phi)}{V(\phi)} \right)^2 \right]$

For inflation to last for many e-foldings, first and second derivatives of the potential must be small, which implies

$$(n_s - 1) \lesssim \text{few} \times 10^{-2}$$

Generation of perturbations

Inflationary model: $S = \int d^4x \sqrt{-g} \left(\frac{1}{2}(\partial\phi)^2 - V(\phi) \right)$

[with dynamical $g_{\mu\nu}$]

"Tensor perturbations": at the end of inflation, there is a stochastic background of gravity waves with power spectrum

$$P_{\rm gw}(k) = r A_\zeta \left(\frac{k}{k_0} \right)^{n_t - 3} \qquad r = \text{"tensor-to-scalar ratio"}$$

$$r = 8 M_{\rm Pl}^2 \left(\frac{V'(\phi)}{V(\phi)} \right)^2 \qquad n_t = -r/8$$

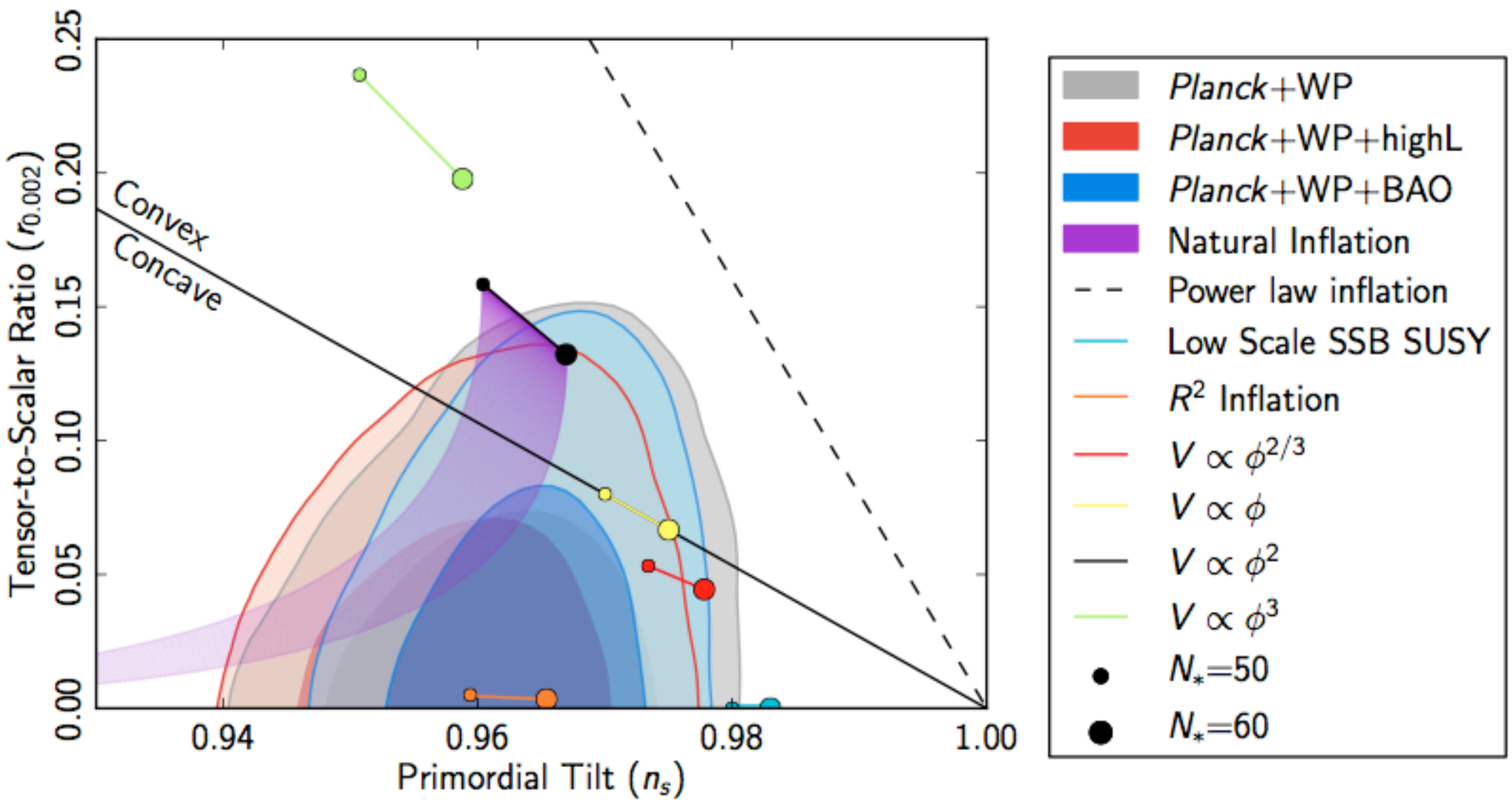
For a "generic" potential, $r \sim 0.1$ which is detectable!

.... but energy scale of inflation is $(3 \times 10^{16} \text{ GeV}) \times r^{1/4}$
so detectable r corresponds to fine-tuned energy scale ... ?

Planck constraints

Many inflationary models can be compared to Planck data by simply locating them in the (n_s, r) plane

$$P_\zeta(k) = A_\zeta \left(\frac{k}{k_0}\right)^{n_s-4} \qquad P_{\mathrm{gw}}(k) = rA_\zeta \left(\frac{k}{k_0}\right)^{-3-r/8}$$



Planck constraints

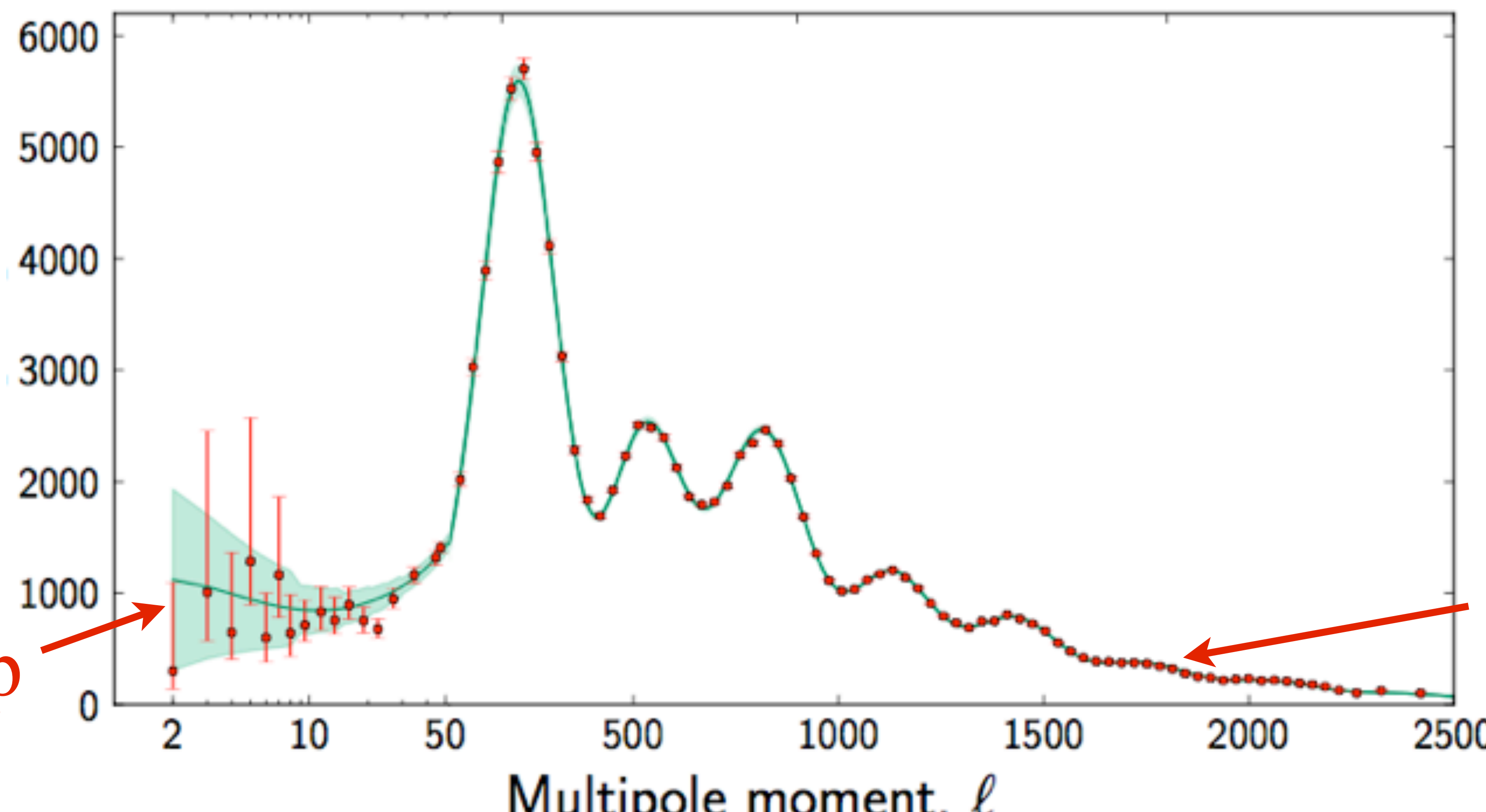
"Running" spectral index parametrizes deviation from power law

$$P_\zeta(k) = A_\zeta \left(\frac{k}{k_0}\right)^{n_s - 4 + \frac{dn_s}{d\log k}\log(k/k_0)}$$

Single field slow roll predicts $dn_s/(d\log k) \approx 0$

Planck constraint: $-0.031 < dn_s/(d\log k) < 0.002$

(Weak) preference for negative running comes from "dip" at low l



$\ell = 20$ dip
2-2.5σ

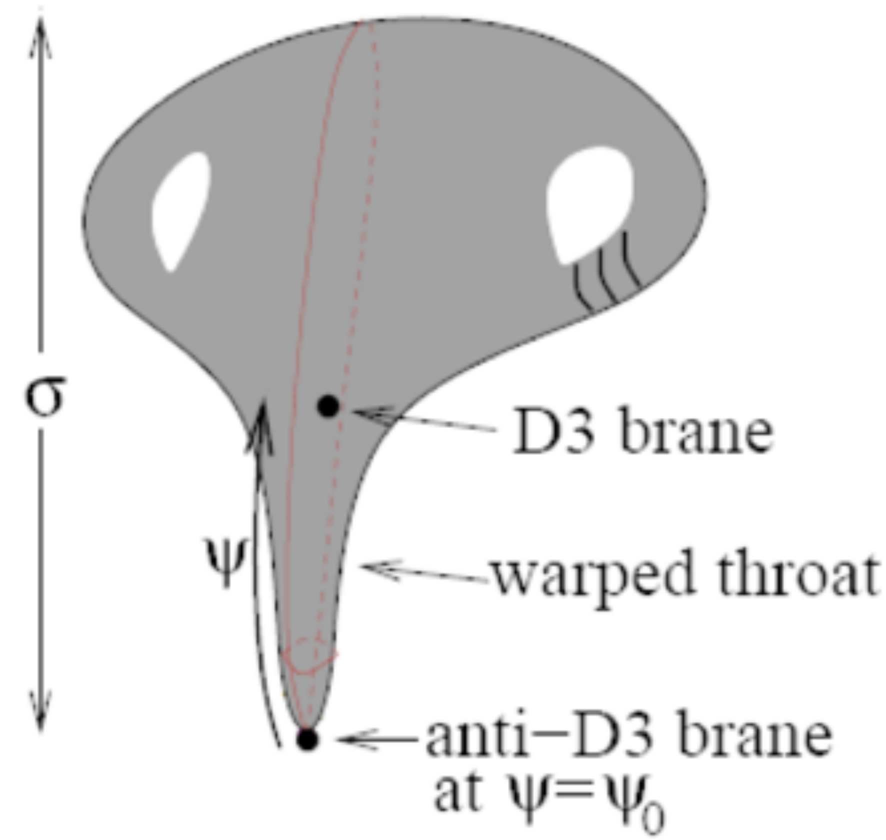
$\ell = 1800$ dip
2.5-3σ

Primordial non-Gaussianity

Example model: DBI inflation

String-motivated model of inflation
(Alishahiha, Silverstein & Tong)

$$\mathcal{L} = -\frac{1}{g_s}\left(\frac{\sqrt{1+f(\phi)(\partial\phi)^2}}{f(\phi)} + V(\phi)\right)$$



After a suitable change of variables, the effective action can be approximated as a massless scalar with a $\dot{\sigma}^3$ interaction

$$S = \frac{1}{2}\int d\tau\, d^3x\, a(\tau)^2 \left[\left(\frac{\partial\sigma}{\partial\tau}\right)^2 - (\partial_i\sigma)^2\right] + f\,a(\tau)\left(\frac{\partial\sigma}{\partial\tau}\right)^3$$

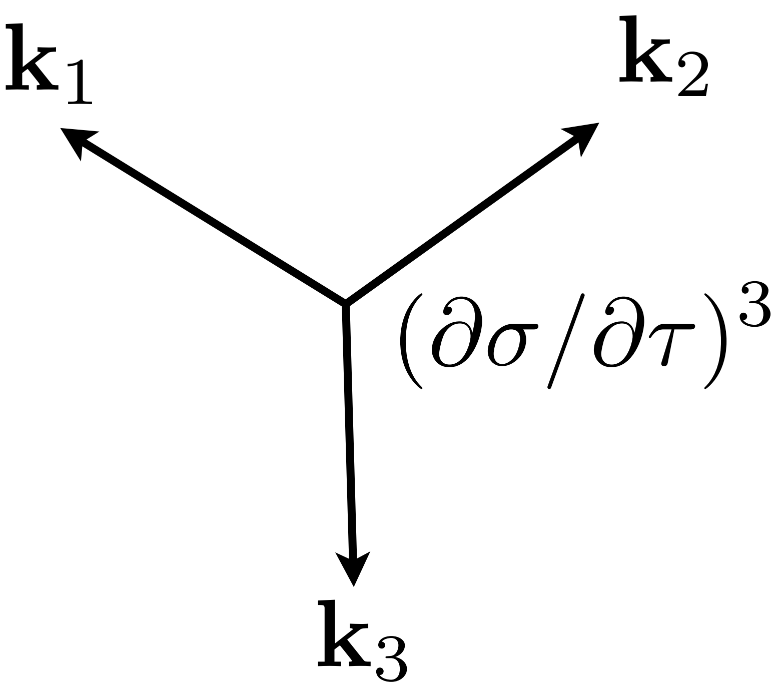
small coupling constant

Primordial non-Gaussianity

DBI example:

$$S = \frac{1}{2}\int d\tau\, d^3x\, a(\tau)^2 \left[\left(\frac{\partial\sigma}{\partial\tau}\right)^2 - (\partial_i\sigma)^2\right] + f\, a(\tau)\left(\frac{\partial\sigma}{\partial\tau}\right)^3$$

To first order in f, non-Gaussianity shows up in the 3-point function

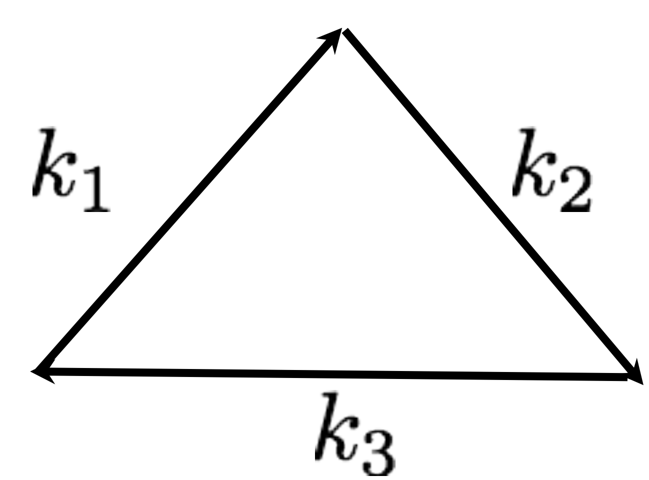


$$\langle \zeta_{\mathbf{k}_1}\zeta_{\mathbf{k}_2}\zeta_{\mathbf{k}_3}\rangle \propto f\int_{-\infty}^{0} d\tau\, \frac{\tau^2 e^{(k_1+k_2+k_3)\tau}}{k_1k_2k_3}$$

$$= \frac{2f}{k_1k_2k_3(k_1+k_2+k_3)^3}$$

Signal-to-noise comes from equilateral triangles

Cosmologists' terminology: $f = f_{NL}^{\text{equilateral}}$



Primordial non-Gaussianity

Planck: no evidence for primordial non-Gaussianity

$$f_{NL}^{\rm equil} = -42 \pm 75 \;\; (1\sigma)$$
$$f_{NL}^{\rm orthog} = -25 \pm 39$$

Models with self-interactions of the inflaton (e.g. non-canonical kinetic terms)

$$f_{NL}^{\rm local} = 2.7 \pm 5.8$$

Multifield models of inflation

Normalization: $f_{NL} \sim 1$ corresponds to deviations from Gaussian statistics of order ~(few $\times 10^{-5}$)

Planck sees primordial fluctuations which are Gaussian to one part in 10^3–10^4, an extremely precise test of the predictions of single-field slow roll inflation.

1. Gravitational lensing

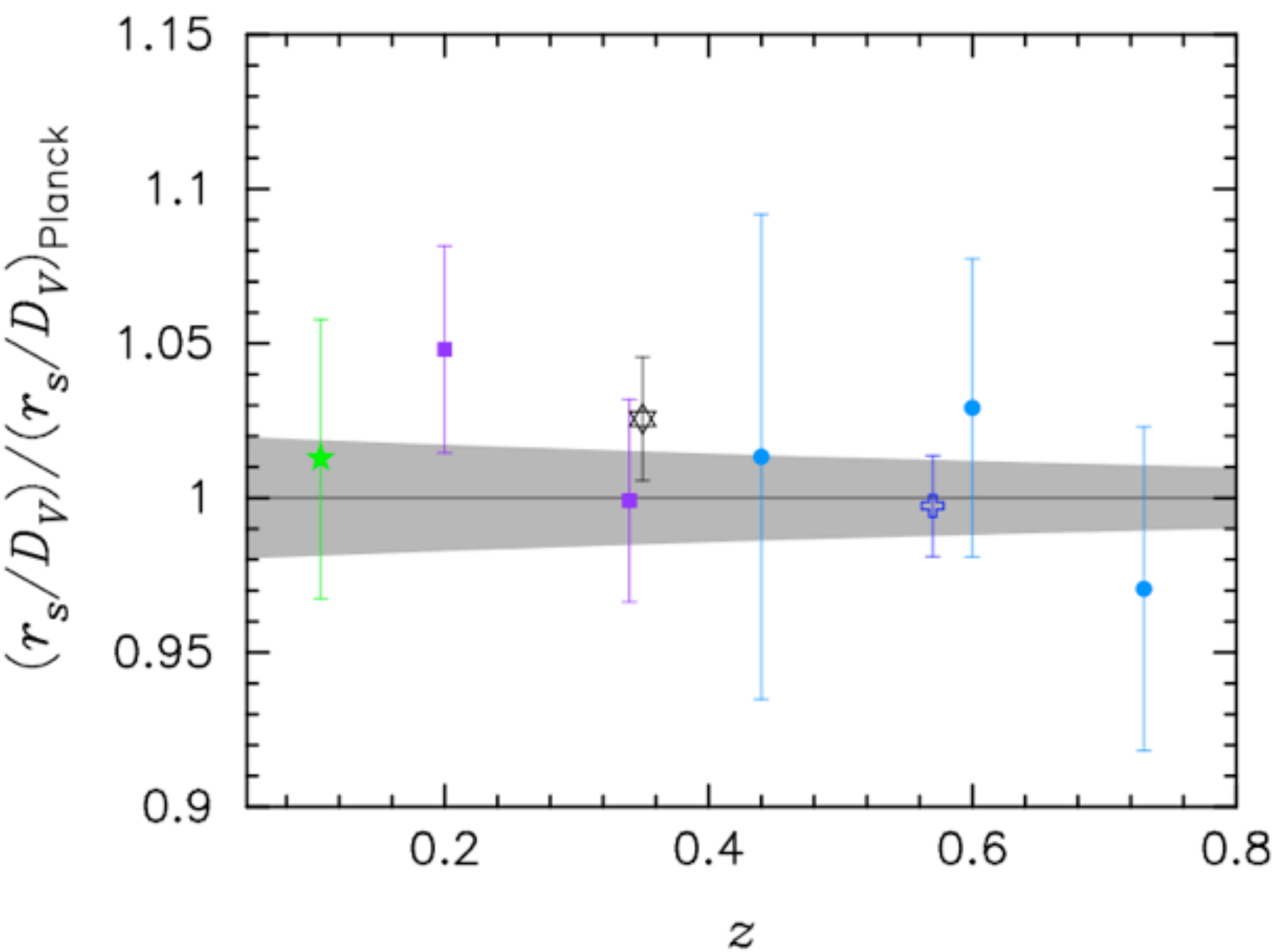
2. Inflation

3. Tension with standard model, or with other experiments

Expansion history

Planck alone constrains the expansion history to ~1%, assuming the standard model. Let's compare to astrophysical measurements...

Baryon acoustic oscillations are very consistent



Expansion history

There is some tension (at the ~1% level) with astrophysical measurements of the Hubble constant H_0

Planck: $H_0 = (67.3 \pm 1.2)\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$

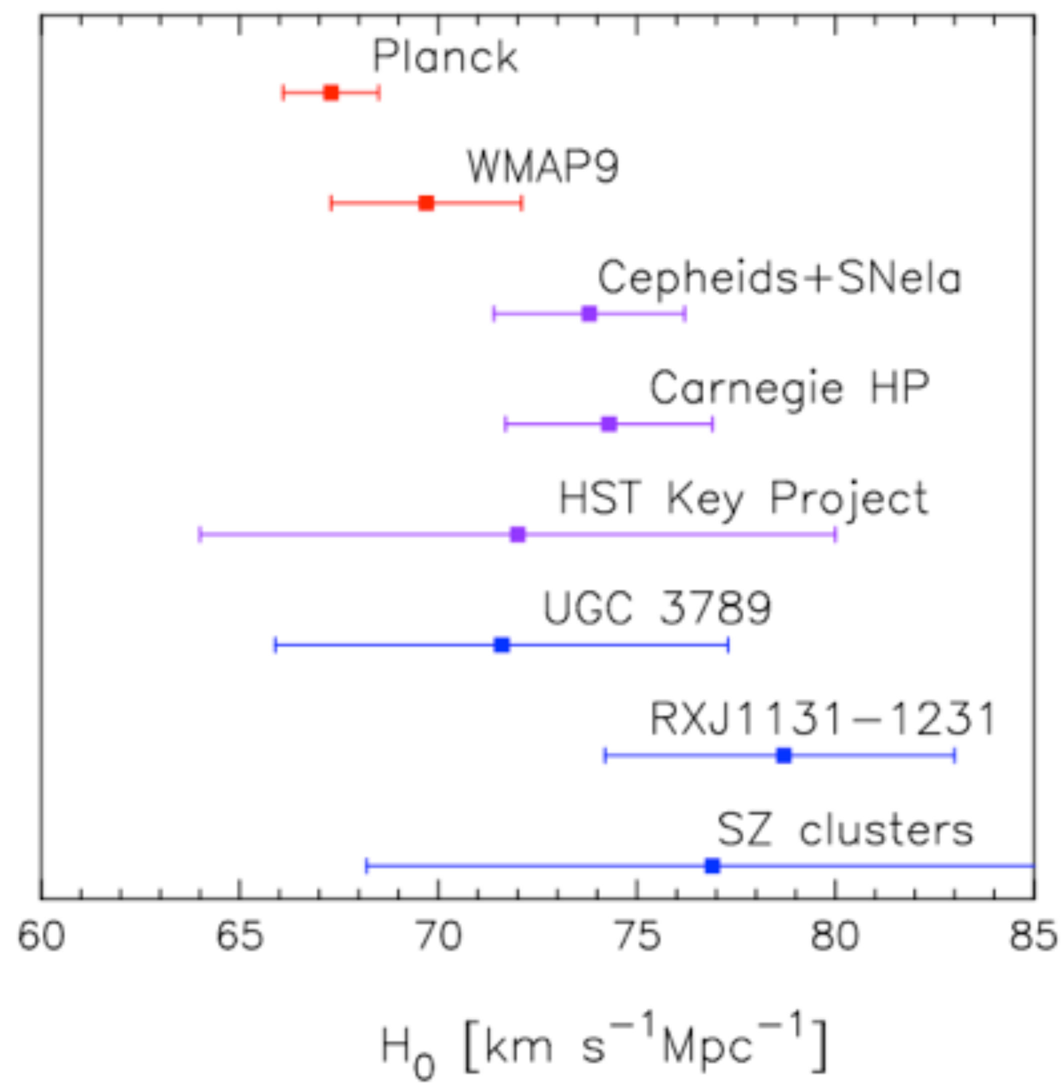
Cepheid-based measurements:

$$H_0 = 73.8 \pm 2.4$$

(Reiss et al)

$$H_0 = 74.3 \pm 1.5(\mathrm{stat}) \pm 2.1(\mathrm{sys})$$

(Freedman et al)



Neutrino mass

Neutrino oscillation experiments measure Δm_ν^2 between species

Current analysis of world data:
$$\Delta m_{31}^2 = (0.049 \pm 0.0012\ \mathrm{eV})^2$$
$$\Delta m_{21}^2 = (0.0087 \pm 0.00013\ \mathrm{eV})^2$$

Cosmology is complementary: lensing is mainly sensitive to $\sum_\nu m_\nu$

Cosmological upper limit (Planck + WMAP-pol + ACT/SPT + BAO):

$$\sum m_\nu < 0.230\ \mathrm{eV} \qquad (95\%\ \mathrm{CL})$$

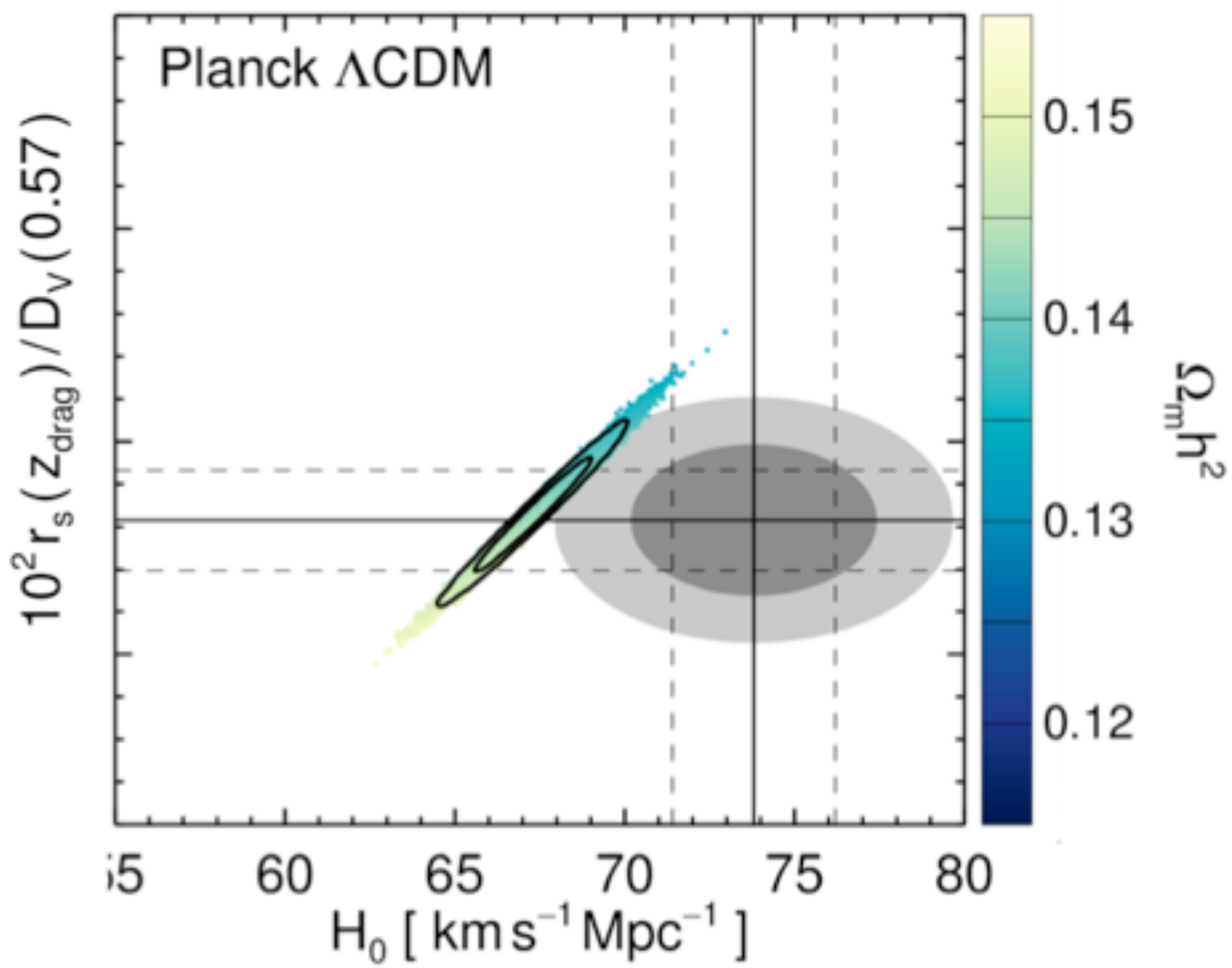
Minimum mass is ~0.06 eV; we are approaching the guaranteed signal

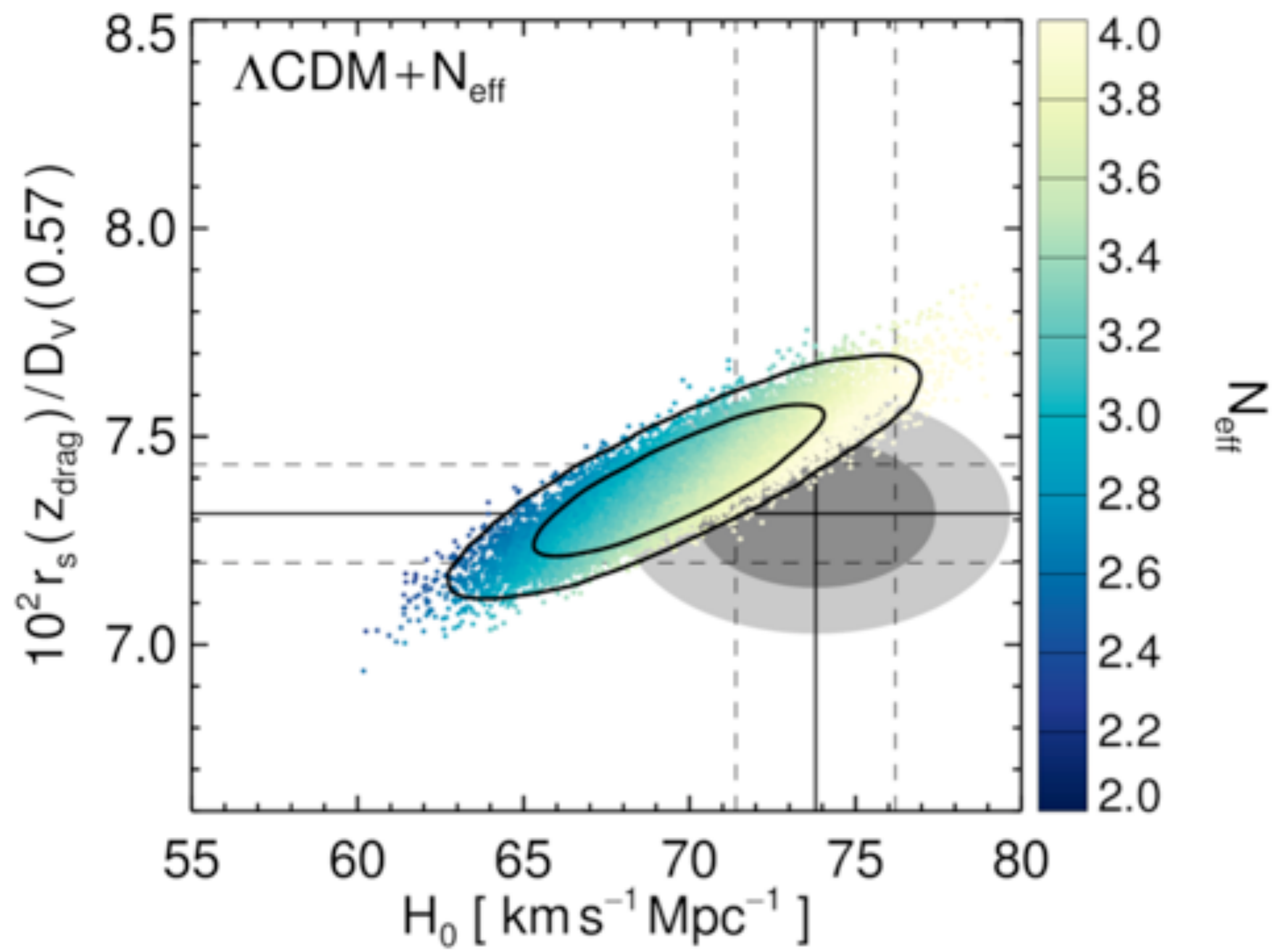
Number of neutrino species

$$2.79 < N_{\rm eff} < 3.84 \qquad (95\%,\ \mathrm{CMB} + \mathrm{BAO})$$

$$3.14 < N_{\rm eff} < 4.12 \qquad (95\%,\ \mathrm{CMB} + \text{astrophysical } H_0)$$

$$3.07 < N_{\rm eff} < 4.00 \qquad (95\%,\ \mathrm{CMB} + \mathrm{BAO} + \text{astrophysical } H_0)$$





Tension with low z?

Compared to some recent experiments which measure growth of structure at low z, Planck prefers

- High Ω_m $(\Omega_m = 0.308 \pm 0.010)$
- Low Hubble parameter $(h = 0.678 \pm 0.0077)$
- Large matter fluctuations $(\sigma_8 = 0.829 \pm 0.012)$

E.g. CFHTLS (gravitational lensing of galaxies) finds

$$\Omega_m = 0.255 \pm 0.014$$

$$h = 0.717 \pm 0.016$$

(CFHTLS + WMAP7)

which is discrepant at the 3-4σ level

Tension with low z?

Internal discrepancy: using the Planck maps, one can count galaxy clusters, via the Sunyaev-Zeldovich effect (Compton scattering of CMB photons by hot electrons). This constrains the combination:

$$\sigma_8(\Omega_m/0.27)^{0.3} = 0.79 \pm 0.01 \qquad \text{(Planck SZ)}$$

But the Planck CMB measurements give

$$\sigma_8(\Omega_m/0.27)^{0.3} = 0.87 \pm 0.02$$

which is discrepant at $\sim 3\sigma$

Conclusions

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  Large-scale structure: expansion history and growth at low z